QUALITY CONTROL
IN
PRODUCTION

QUALITY CONTROL IN PRODUCTION

A MACHINE-SHOP MANUAL ON THE STATISTICAL METHOD OF CONTROLLING PRODUCT QUALITY DURING MANUFACTURE

by

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FOREWORD

by

Sir Frank Gill, K.C.M.G., O.B.E., M.I.C.E., M.I.E.E.

"Quality Control" was a wartime title used in Great Britain to denote the statistical method of interpreting certain data as a basis for action. At that time a pressing need was felt for increased production and it was considered that a good deal of increase in effective production could be obtained by cutting out the waste in materials, man-hours, machine-hours, etc., caused by the manufacture of defective parts, i.e., rejects, and the further waste caused in the rectification of some of the rejects. At that time, too, it was judged that the addition of the qualifying word "statistical" would cause an element of inhibition in factories.

Mr. Rissik was one of the early workers in the application in engineering machine shops of the method he writes about, and he continued to devote his main attention to this subject over the period September, 1940, to December, 1944. During this time he wrote many technical articles and gave many talks to Institutions, Technical Colleges and Engineering Shops; in fact, to any place which applied for assistance. Fig. 2 shows one of the results which came from him, but I pick out that particular illustration because it was the first aggregate result from any machine shop of which I have knowledge The year in which this result was achieved was 1941.

The Author has shown himself to have a knowledge of statistical methods, while still holding firmly to the necessity for production; hence his teaching is balanced and a sane guide.

The technique underlying "Quality Control" is far reaching and applies to the interpretation of data. In certain work it is the only method which can give safety, e g, in the inspection of articles of which the test must be destructive. While the use of the method covers a much wider field, yet this book should form a very useful manual for the particular area it covers, and as an introduction to the many other areas into which earnest students will wish to penetrate

PREFACE

THE rapidly growing and increasingly widespread interest in the application of statistical methods to the control of product quality in repetitive manufacture has led to a demand on all sides for a general handbook on QUALITY CONTROL, as this industrial technique has come to be termed. In fact, so many general engineering and similar manufacturing organisations are now taking active steps to try out and eventually establish systems of Quality Control in their machine shops that the need for some authoritative guidance in the practical applications of this new technique is becoming an urgent necessity.

It is too much to ask that, under present-day conditions, works inspectors and production engineers should be called upon, single-handed and with no experience to draw upon except that contained in the inadequate literature hitherto available, to put into immediate practice new methods based upon unfamiliar principles. They have already a sufficiently heavy load to carry nowadays without being burdened with the effort of making such an attempt. Yet in a great many cases they are willing and even anxious to do so in view of the known benefits that Quality Control has to confer upon the manufacturing organisation which succeeds in making this technique part and parcel of its machine-shop routine.

The position of such engineers has been made a little easier during the last few years thanks to the training facilities offered, on the one hand, by the Ministry of Labour's two staff colleges established at the Waddon and Leeds government training centres and, on the other hand, by the many Technical Colleges throughout the country. There special lecture courses on Quality Control have been held from time to time for the instruction of technical staffs of local engineering firms, ordnance factories and government inspection authorities, and these courses have proved to be of great help in familiarising engineers with the general methods underlying this new technique. But, as the author is only too well aware from his own experience, it is quite impossible to do more than outline the many practical applications of Quality Control in the course of, say, four or five weekly evening lectures at a local technical college.

The present work, therefore, aims not merely at filling in the inevitable

gaps in such a specialised lecture course, but rather at providing the hard-pressed engineer with a more or less complete and self-contained handbook on Quality Control as applied to production. It will thus serve him as a useful practical textbook to which he can turn for guidance in tackling the many problems which he will have to face when trying to introduce a quality control system into a manufacturing organisation At the same time it will help him to reach a more rapid understanding of the basic principles of Quality Control if and when he takes the opportunity of attending a course of lectures on the subject.

Finally, it is the author's hope that his treatment of this new engineering technique will tempt the practical man of an engineering turn of mind to venture a little farther into the realm of industrial statistics. Engineers, unfortunately, have not been made to realise the immense value of statistical methods in matters of design, testing, production and inspection. This is very largely the fault of the statisticians, who have failed to bring their subject down from the academic heights to the practical levels occupied by the engineers. There is no need for an engineer to try and become a statistician. Even where he has the mathematical ability he hasn't got the time. But he can learn to *use* statistical tools—many of them are as simple to apply as Quality Control—and will find himself to be a better engineer as the result. As Lord Kelvin once remarked : "There is no useful mathematical weapon which an engineer may not learn to use."

The author wishes to acknowledge his indebtedness to the following firms for much of the information given in Chapter VI . The Bristol Aeroplane Co., Ltd. ; Creed & Co., Ltd. ; Philips Lamps, Ltd. , and Standard Telephones & Cables, Ltd.

H. RISSIK.

HURLINGHAM.

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INTRODUCTION

The importance of Quality Control as a manufacturing aid to be fostered and developed as part of our general production effort has long received official recognition. Early in the summer of 1943 the Ministry of Production issued, through the medium of its Regional Organisation, a leaflet on Quality Control which aimed at stimulating the interest of manufacturers in what is undoubtedly proving to be one of the greatest of recent advances in production technique. As a result, the Birmingham District Production Committee of the Ministry set up a Quality Control Panel which was conspicuously successful in its educational and advisory work among engineering and other firms in the Midland Region.

The evidence so far available in the engineering industry goes to show that this latest technique provides the only sound means of restoring the sense of craftsmanship to our engineering production, and thus of attaining the high standards of quality so necessary to-day, without the aid of ever-increasing inspection staffs. The production drive still calls simultaneously for *more* output, and *less* waste of materials, man-hours and machines. It will be recalled that the Minister of Production himself drew public attention to this urgent two-fold need in Parliament towards the end of 1942.

Quality Control directly attacks waste. It leads to a better quality product through the reduction of scrap, and to smoother production through minimising the effort wasted in producing semi-faulty material which has to be corrected in order to be made usable. At the same time Quality Control in most cases achieves this desirable result with less aggregate inspection effort per unit of output.

The purpose of this Introduction is to summarise, for the benefit of readers wanting a simple and non-technical explanation, the features of quality control technique discussed in the present book. For convenience the summary is given in the form of a questionnaire with appropriate replies. In the author's experience the questions given below are those almost always asked by management when approached by technical men trying to sell the idea of Quality Control as an aid to production.

(1) What is Quality Control?

Put very briefly, Quality Control is a method of charting process inspection data so that visual indication is given of the quality of the product as it is being manufactured, thereby enabling corrective action

to be taken *as soon as* things begin to go wrong with the production process.

The basis of Quality Control as an inspection method is the examination (in a rather special way) of samples of the product at regular intervals *during* the process of manufacture. It is, therefore, in sharp contrast with the normal inspection of finished products, which results merely in the throwing out of defectives. Quality Control is designed to avoid the *making* of these defectives

Hence Quality Control makes the inspector's function essentially *active* and *productive*; instead of, as hitherto, passive and non-productive. The use of quality control charts in the machine shop focuses the attention of all concerned on the production process rather than on the resulting product.

(2) What are its Advantages?

Quality Control directly attacks waste. It enables a manufacturer to minimise (*a*) the costs he incurs through rejections, and (*b*) his inspection costs.

By taking appropriate action as and when indicated by the quality control chart, the manufacture of defective products can be prevented. As a result, inspection of the product between successive process operations can be dispensed with. For example, a precision engineering firm in the North London area has since January, 1943 (when Quality Control was introduced) been passing out "quality controlled" components direct, i.e., without any subsequent inspection whatsoever, to the I.N.O. authorities at the rate of over 100,000 per week (See Chapter II.)

In addition to these two major benefits—reduced defective product and reduced inspection effort—Quality Control has a beneficial effect on machine-shop production generally. By introducing "mass craftsmanship" into mass production it makes the rank-and-file production personnel interested in their job. Tool-setters and machine-shop operatives actually take an interest in the quality control charts posted alongside their machines. The use of control charts has led to competition between individual operatives or groups of operatives, between tool-setters, and between day and night shift production personnel. In some instances "quality bonus" schemes, based on the control chart records, have been introduced as a direct incentive to improved production, and these have proved highly successful. (See Chapter VI)

Finally, the introduction of Quality Control will lead to reduced inspection by the purchaser or his agent. In fact, where control chart

records of production processes are by agreement made available by the manufacturer to the purchaser, the latter may dispense with 100 per cent. inspection of the product. This system of "acceptance tests" based on the manufacturer's evidence of controlled quality, instead of on the results of the purchaser's own inspection, was beginning to be adopted during the later war years by the C.I A All such reduced customer inspection ultimately benefits production in that it avoids "inspection bottle-necks."*

(3) Is Quality Control merely a War-time Experiment or Expedient?

The statistical method of controlling product quality during manufacture—commonly termed Quality Control—was originated in 1924 by Dr. W. A. Shewhart of the Bell Telephone Laboratories in New York. It has been used in this country for many years in electric lamp manufacture and in certain branches of the textile and chemical industries. In the field of production engineering it is, however, a very recent development and may be said to date from the latter part of 1940. Since then the technical development of Quality Control has been rapid and many improvements in the original Shewhart technique, appropriate to machine-shop applications, have been made.

The ultimate aim of Quality Control is to provide an economic means of attaining, maintaining and checking objective standards of quality. This is of great importance to our post-war export trade and is the reason why, for example, the British Standards Institution takes such an active interest in the development of quality control methods in industry.

(4) Where is Quality Control Applicable?

Broadly speaking this new inspection technique is applicable only to manufacturing units organised on a quantity or mass production basis. Wherever production is repetitive, either in a continuous flow or batch by batch, there quality control will prove to be of ultimate benefit. As a matter of experience it is found that the method is not economic if an individual batch runs for less than two 10-hour or three 8-hour shifts through the production process to be "quality controlled" There are

* The subject of quality control methods as applied to *product* inspection (as distinct from *process* inspection) is beyond the scope of this book. An account of such methods of so-called Acceptance Control was given by the author in an address to the Institution of Engineering Inspection on 15th April, 1943. This address, under the title "Quality Assurance through Sampling Inspection," was published in *Engineering Inspection*, 1943, Vol. 8, No. 2, pp. 12-29, and in *Aircraft Engineering*, 1943, Vol. 15, No. 171, pp. 149-152, and No. 172, pp. 179-182.

exceptions, of course. Where small batches repeat constantly, e.g., in aircraft production on short orders, Quality Control is still applicable. (See Chapter VI.) The original application of Quality Control to a machine shop in this country took place in a precision engineering firm where the average batch size was around 500-1,500 piece parts.

The basic control chart methods are also applicable to product inspection, as distinct from process inspection. It is in this sphere, rather than in that of Quality Control proper, that the use of these methods leads to the greatest economies in inspection effort and, therewith, to corresponding savings in man-power.*

(5) How does Quality Control affect the Existing Organisation of Production within the Manufacturing Unit ?

It directly affects the inspection side of the organisation in that it is essentially a new inspection technique which involves the systematic recording and charting of process inspection results

It directly affects the machine-shop side of the organisation in that operatives, tool-setters and similar production personnel are given objective quality standards to which to work ; and in that they can see for themselves (on the quality control charts) whether or not they are succeeding in maintaining these standards.

It indirectly affects (*a*) production planning and (*b*) engineering design in that the quality control charts provide concrete evidence as to whether or not a particular production process is inherently capable of meeting specified tolerance limits. This unique feature of the quality control method is in practice almost as valuable as the minimising of both defective work and inspection costs. (See Chapter IV.)

(6) What bearing has the Introduction of a system of Quality Control on the Attitude of Government Inspecting Authorities ?

Official inspection bodies like C.I.A., I.N.O. and A I.D. are nowadays sympathetic to this new technique. In fact, where a firm introduces Quality Control, they are generally prepared to reduce the amount of inter-process inspection carried out either by themselves or under their supervision.

In certain regions the C.I.A. have considered the acceptance of the manufacturer's control charts as evidence of product quality, in lieu of 100 per cent. inspection of the product. The A.I.D. have in certain instances agreed to a manufacturer using a statistically designed " double-

* See footnote on previous page.

sampling inspection plan" instead of 100 per cent. inspection of certain finished components.

(7) How does Quality Control differ from existing Methods of Inspection ?

By focusing attention on the *pattern* of the observed results of inspection, rather than upon the number of defective items produced, the quality control method enables one safely to judge the quality of the mass of product submitted for inspection by examining relatively small samples instead of all items in the mass.

Quality Control thus involves a systematic *sampling inspection* of the product during manufacture, in place of the usual 100 per cent inspection of the product between processes (with or without casual patrol inspection of the processes themselves).

The sampling inspection results are plotted, *as soon as they are obtained*, on the quality control chart which is kept adjacent to the machine performing the operation to be controlled. The control chart thus furnishes a continuous graphical record of product quality during manufacture and provides a readily understood, visual means of judging significant deviations from standard quality. By taking appropriate action as indicated by the control chart, any tendencies making for defective production can be anticipated and corrected *before* the defectives are actually produced.

Traditional inspection methods only enable one " to be wise after the event." Quality Control serves to make one " get wise before the event."

(8) What are, very briefly, the Operational Principles of the Quality Control Method ?

There are two basic systems of Quality Control in common use, namely, Quality Control by (*a*) measurement and (*b*) counting defectives. The former is always to be preferred as it is the more efficient method of minimising defective production, but there are certain situations in which it is inapplicable.

(*a*) *Quality Control by Measurement.* By analysing the measured results of sampling inspection (i.e., systematic patrol inspection) and by promptly studying the pattern of these measurements (i.e., the relevant control chart), one is able to take such preventive action as will remove trouble-making causes *before* defective items are actually produced. (See Chapter IV.)

This method of Quality Control clearly involves the use of suitable measuring equipment, such as micrometers, dial gauges or comparators.

In the case of certain firms, particularly those making components under sub-contract, this requirement may be a limiting factor in quality control development.

(b) *Quality Control by Counting Defectives.* By analysing the number or fraction of defective items, i.e., items which fail to meet specification limits, produced during manufacture, in cases where measurement is either inapplicable (e.g., visual inspection, small bores, internal screw threads) or else uneconomic (e.g., fast production and multi-dimensional checking by limit gauges), and by promptly studying the pattern of such defective production, i.e., the relevant control chart, one is able to take such preventive action as will remove trouble-making causes *before* they give rise to an increased rate in the production of defective items. (See Chapter V.)

This method of Quality Control is based on the use of existing limit gauges (" go " and " not go " gauges, etc). A very recent modification enables direct control of dimension to be obtained, thus making the method approach method (a) in sensitivity.

(9) What type of Labour is required to Operate a System of Quality Control ?

The quality control method has the supreme merit of simplicity. The construction and maintenance of control charts involve only the simplest arithmetic. Experience has amply proved that female inspectors, properly trained, are quite capable of dealing with the sampling inspection routine and the plotting of the appropriate control charts. (See Chapter VI.)

The general preparation of blank control charts, the drawing up of quality control data sheets, and other records of a supervisory character are generally dealt with by a small clerical staff on each shift.

(10) How should a System of Quality Control be Introduced ?

It is *not* necessary or even desirable, except perhaps in the case of a large manufacturing organisation with several dispersed factories, to set up a distinct quality control organisation. The usual procedure is for the Works Manager or Chief Inspector to nominate a member of his technical staff to develop the applications of Quality Control. This nominee should thereupon :—

(a) study the available literature (see Appendix A) ;
(b) visit firms who are already using Quality Control, and preferably those using it as part and parcel of their machine-shop routine ;

(c) attend, if possible, one of the special part-time courses on Quality Control run from time to time by local technical colleges and engineering societies.

The next step is to select one or two machine-shop processes that are habitually troublesome (i.e., productive of defective piece parts) and to run Quality Control on an experimental basis *in parallel with the existing inspection routine* In this way experience can be gained without interfering with the existing organisation. In most cases it will be found that the results under Quality Control justify the reduction, if not the abolition, of detail inspection of the product between the various manufacturing stages (process operations).

As soon as a sufficient weight of evidence has been gained in this way to show that Quality Control does benefit production, little difficulty will be found in persuading the management to introduce Quality Control as a routine procedure in the machine shop.

(11) Where can Assistance and Advice be sought in case of Difficulty ?

In most cases individual difficulties with quality control applications can be overcome by discussing the problems with engineers of other firms already using this new system of inspection.

In some cases it may be possible to obtain assistance from the engineering department of the local technical college or through the secretary of a local engineering society.

In all cases an approach to the secretary of the Industrial Applications Section of the Royal Statistical Society (2 Portugal Street, London, W.C.2) should prove helpful in making contacts with industrial undertakings already using Quality Control and allied statistical techniques. The Section, which was formed in 1945, so far comprises three regional Groups, with headquarters in London, Birmingham and Sheffield, whose members are largely recruited from men with practical experience of statistical methods in a wide range of industries. The Groups hold regular meetings which are mainly devoted to discussion of Quality Control and Acceptance Control problems, and which are open to anyone interested in the industrial applications of statistical methods.

CHAPTER I

STATISTICAL METHOD AND THE QUALITY PROBLEM

VERY few engineers have any knowledge of, let alone any kind of training in, statistical methods. In fact, most people look upon statistics as something dry and indigestible for which only economists, biometricians, and certain types of bureaucrats have been given the necessary stomachs. Mark Twain once went so far as to declare that those who fail to speak the truth can be classed in three categories: liars, damned liars, and statisticians! The fact remains, however, that statistics is a science of very great importance. Its foundations are as securely established as those of any other of the recognised sciences, and its structure often forms an integral part of the application of such sciences to the solution of practical problems. As a matter of fact, the statistician has had more influence on modern developments in such fields as agriculture and biology than has the agronomist or biologist himself, while his analytical methods have become so potent that statistical technique is nowadays regarded as an essential element in scientific research. In fine, statistics has become eminently respectable.

Why should engineers concern themselves with statistical methods? For several reasons—some general, some particular. Among the general reasons is that given by Shewhart: "The basic contribution of statistics to the science of engineering is an improved scientific method to fit the world of probability in which we live."* In other words, the fundamental difference between engineering with and without statistics boils down to the difference between (1) the use of a scientific method based upon the concept of natural laws that are fixed and rigid and which thus do not allow for chance or uncertainty, and (2) the use of a scientific method based upon the concept of probability as a fundamental and characteristic attribute of Nature.

Among the particular reasons why engineers should no longer be ignorant of statistical methods is that which led to the conference held on 15th April, 1942, in London by the Institutions of Civil, Mechanical, and Electrical Engineers under the somewhat forbidding title of "The

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* W. A. Shewhart, "The Contribution of Statistics to the Science of Engineering" (an Address delivered to the Bicentennial Conference of the University of Pennsylvania at Philadelphia in September, 1940), *Metal Progress*, June, 1942, pp. 854-858.

Application of Statistical Control of the Quality of Materials and Manufactured Products."* For the statistical method of quality control constitutes a technique for so modifying and co-ordinating the three fundamental stages in the process of mass production, viz., specification, manufacture and inspection, that the maximum amount of product having a quality within specified tolerance limits can be turned out at a given cost. In other words, this new method enables a manufacturer to minimise (1) the costs he incurs through rejections, and (2) his inspection costs. Not for nothing did *The Times* in its leader of 16th April, 1942, refer to Quality Control as "taking its place as a war-winning method of maintaining the standard of production and the prevention of waste."

Quality Control and Engineering Practice. The statistical method of controlling product quality during manufacture—a technique commonly known by the shorter title, Quality Control—is a very recent development in the field of production engineering. In point of fact the first application of this technique to machine-shop production in this country was undertaken by the author late in 1940 at the Croydon works of Messrs. Creed & Co., Ltd., a firm whose name is a household word in electrical communication, for the Creed teleprinter is known all over the world.† At the same time it must not be thought that Quality Control as such, or the use of the so-called quality control chart as an aid to manufacture, was a purely wartime development. Statistical methods, including Quality Control, have been employed in British industry, notably in electric lamp manufacture, and in the production of both cotton and woollen textiles, for more than fifteen years, whilst the technique of Quality Control itself was originated by Dr. W. A. Shewhart of the Bell Telephone Laboratories, New York, in 1924. But where engineering practice was concerned, the application of statistical methods did not present itself until quite recently as a necessary or even convenient solution of manufacturing difficulties.

That this should be so is, after all, not surprising. Unlike the textile and chemical industries, for example, or agriculture—the sphere of statistical method *par excellence*—the engineering industry is characterised by technological processes which can be specified in precise terms. As a result, product quality is subject to a very high degree of control, inherent in these processes, and is only to a small extent influenced by

* See *Proceedings of the Institution of Mechanical Engineers*, 1942, Vol. 147, No. 3, pp. 125-144.

† See *Machinery*, 30th June, 1942, p. 118; and *ibid.*, 13th August, 1942, p. 169.

factors that give rise to uncontrolled variations. At the same time the quality safeguard provided by individual craftsmanship has vanished from the sphere of engineering production, and hence there is no longer any guarantee that the products of highly mechanised manufacturing processes will maintain quality levels on a par with the high levels of output commonly associated with mass production methods. This implied contradiction between the " quantity " and " quality " aspects of production engineering, however, has only emerged during the recent war years as a practical problem demanding a satisfactory and lasting solution. That solution has happily been found in the statistical method of Quality Control.

The Great War saw the disappearance, for better or worse, of the old-time engineering craftsman whose traditional skill and knowledge at one time made this country " the industrial workshop of the world." Instead there arose, as the direct result of the needs of the 1914-1918 conflict, a new tradition of mass production with its own specialised skills at the higher organisational levels and its reliance upon semi-skilled and even unskilled labour as the operative factor in the new production processes. This new tradition has been one in which all the emphasis is placed on " production methods," whereas in the past the emphasis lay on " workmanship." During the past thirty years, therefore, it has been felt that the new engineering automatically took care of the quality of the product along with the quantity. There was never any thought that uncontrolled factors of any serious importance to product quality lay concealed in the superlatively mechanised and highly precise manufacturing processes which are characteristic of modern production engineering.

In the event this rather complacent view proved to be false. More and more inspection of the products of mass manufacture became necessary as engineering ingenuity combined with scientific management raised output to ever higher levels. It became increasingly clear that mass production methods were but a poor substitute for the craftsmanship of the bygone file-and-chisel era. In consequence the emphasis in production to-day is on methods *plus* workmanship, that is to say, on quantity *and* quality. The production drive during the present era of rehabilitation calls simultaneously for *more* output, and *less* waste of materials, man-hours and machines.

It is just here that the technique of Quality Control comes into its own. For it constitutes the only available means of introducing " mass craftsmanship " into mass production, of ensuring that the desired quality

is actually built into the product as it is being manufactured. Quality Control, as its name implies, is essentially a method of *controlling* the quality of a product *during* manufacture It is this characteristic feature of the new technique which distinguishes it so sharply from traditional production methods involving large-scale product inspection, and thus relying on quality *determination* of the product *after* manufacture. Thus, wherever Quality Control has been introduced into a production engineering organisation, its first effect has been to reduce not only the amount of scrap produced but also—and this is even more important—the productive effort wasted in turning out semi-faulty material which has to be corrected afterwards. In not a few cases this desirable result has been achieved with less aggregate inspection effort per unit of output, *for Quality Control removes the deadweight on production of* 100 *per cent. inspection between process operations.* This deadweight is a legacy from the recent past, with its emphasis on production methods as such and its implicit view of inspection as a non-productive screening operation for sifting out the bad from the good.

Process Inspection as the Basis of Quality Control. When considering Quality Control from the traditional "mass production" standpoint we find that machine-shop practice customarily lays stress on the design of specific production facilities rather than upon any general system, whether of technique or organisation, for maintaining product quality at the desired level. Whilst it is doubtless true that progress in methods of production has played, and continues to play, an important and valuable part in maintaining satisfactory quality standards in the face of an ever-increasing scale of manufacture, yet we inevitably reach a point where it becomes beyond the capacity of any manufacturing planning programme to ensure that an adequate standard of product quality will be consistently maintained. It is when this point is reached that the onus of maintaining product quality, in the face of ever more pressing demands for increased output, tends to fall upon the manufacturer's inspection organisation. We have clearly reached this point already in the field of production engineering, as witness the disproportionately rapid growth of both manufacturer's and purchaser's inspection staffs during the war years.

From a functional standpoint the inspection department's authority and responsibility are customarily limited to the power of either accepting or rejecting product at any stage of the manufacturing process. The control of the factors in that process which ultimately govern the quality of the product lies in the hands of other departments. This functional cleavage between inspection and production is well established and is

sound practice. Modern management rightly condemns the principle of combining these two functions within a common manufacturing group, for under present conditions it is asking for trouble to allow a manufacturing unit to " mark its own copybook." Under these circumstances, then, where inspection and production are distinct functional elements in works organisation, we do not have very far to seek for the reason why the inspector's job is commonly regarded as being non-productive.

The inspector's power to reject unsatisfactory work is, of course, the traditional means whereby some kind of supervision is exercised over product quality. A manufacturing department producing defective work is thereby made to incur expense in respect of scrap and/or rectification, which shows up unfavourably in the departmental operating results and so forces corrective action. This is a rather crude and a very costly way of controlling quality, for it inevitably entails a considerable loss before improvement is effected. Hence the attempt is generally made to obtain a more direct control over product quality. For example, the management may introduce certain penalties into the wage system to act as a check on individual carelessness. Such penalties are commonly limited to non-payment for defective work, or to the requirement that the operator sorts out or makes good the defective items in his or her own time. Measures of this kind, however, are only effective where the responsibility can be definitely fixed. Experience, unfortunately, goes to prove that this situation is the exception rather than the rule. We are thus forced to the conclusion that a close adherence to functional routine provides an inspection organisation with only a limited degree of control over product quality In other words, *inspection by itself does not constitute Quality Control.* Here we see the origin of the widespread belief that inspection is necessarily non-productive.

Yet this belief is erroneous, for it is based on a popular misconception as to the true function of inspection The view commonly prevailing in manufacturing circles, particularly in the engineering sphere, is that the inspection department is concerned solely with discriminating between defective and effective product. As a result, inspection practice degenerates into the mere sorting out of bad work from good at the end of each production process. Such inspection is purely a means of *quality determination* and, as such, is a non-productive operation. It is fairly clear, therefore, that unless and until inspection effort is directed towards the positive control of product quality during actual manufacture, the inspector will continue to be regarded as a brake upon production. Traditional inspection practice fails to realise that one cannot " inspect,"

into a product, quality that was not put there by the manufacturing process in the first instance. The statistical method of process inspection, on the other hand, is primarily a means of preventing or minimising defective work through the interception of tendencies in the manufacturing process to create defective product. Such a method differs radically from traditional inspection practice, with its emphasis on the product rather than on the process, in that it has the power to *control quality.* This technique of Quality Control thus enables the inspection department to exercise its true function, namely, that of assisting the production departments in maintaining a desired level of product quality. In short, it makes inspection productive. For the statistical method of Quality Control is essentially an inspection routine which appears as "a continuing and self-corrective method for making the most efficient use of raw and fabricated materials."

Modern Quality Control Technique. The key to the central problem of controlling the quality of a product during its actual manufacture thus lies with the inspection department. But the mechanism which unlocks the door to Quality Control is a technique designed by the statistician. As with most mechanisms of a sensitive nature, so with this technique the basis of the design is by no means easy to understand unless one is familiar with the theory of mechanisms—in our case the theory of probability as applied to statistical methods. But again, like most mechanisms, the statistical technique of quality control is simple to operate. And as long as one understands the operating rules for the mechanism, one can use it to advantage. So it is with modern quality control technique.

The application of this technique as a part of normal inspection routine is a particularly happy example of the value of graphical methods in solving engineering problems. The inspection department exercises its true function, that of assisting the production departments in maintaining a desired level of product quality, through the medium of the so-called quality control chart which is, in effect, a continuous graphical record of product quality.

From the standpoint of its practical application in a manufacturing organisation the control chart has the supreme merit of simplicity. Like the slide-rule it is an engineering tool in the use of which inspection and production personnel can become, with a little practice, both confident and proficient. This inherent simplicity of modern quality control technique is a feature that cannot be too strongly emphasised. *For the construction of quality control charts involves only the simplest arithmetic*

and is based on formulae derived from the statistical approach to the quality control problem whose reliability has been proved in actual practice over a number of years.

Very briefly, and without embarking on technicalities, the quality control chart provides a visual means of segregating the variations in product quality which are solely due to chance causes, and over which we can therefore exercise no control, from those variations which arise from "assignable" causes, that is to say, from causes which can be assigned to one or more specific physical elements in the manufacturing process. By plotting the successive findings of process inspection on such a chart the presence of one of these latter causes of non-random variation is immediately revealed, so that a search can be made with a view to eliminating it before its operation can give rise to defective items of product.

In the course of time, as these assignable causes of quality variation are gradually eliminated, the manufacturing process is brought completely under control and eventually yields a stable product, that is, one whose variations in quality are entirely of a random nature. When this ultimate goal of Quality Control is attained, the following practical benefits immediately accrue :

(1) The variation between individual items or units of product will be a minimum for the manufacturing process in use.
(2) The percentage of future product whose quality will lie within any specified pair of limits may be predicted with the highest degree of assurance.
(3) A reliable and objective basis is established for determining whether or not any practical advantage would be gained by changing the manufacturing or specification limits laid down for the process in use.
(4) Data obtained from sampling inspection of a product will have the greatest possible reliability as a basis for quality judgments. Sampling and testing, and hence the cost of inspection, can be reduced to a minimum. As a result it follows that sampling inspection (in place of 100 per cent. inspection) is adequate, both for the manufacturer and the purchaser.
(5) Acceptance of a product may safely be based on the manufacturer's evidence of controlled quality as provided by the control chart, rather than upon the results of the purchaser's own inspection. In particular, if continuous control chart records are by agreement made available by the manufacturer to the purchaser,

the latter will then need to test only occasional samples by way of checking the quality records furnished by the manufacturer.

The first three of these advantages will be readily appreciated by engineers concerned with modern production methods. For example, one not infrequently finds cases where there is an insufficient margin between the limits of variation inherent in a production process and the manufacturing limits specified by the design department, so that no scheme of process inspection short of 100 per cent examination of the product can ever be effective. Only a control chart, however, will furnish positive proof that such an unfortunate state of affairs exists, and hence will provide the evidence for altering either the process or the specified manufacturing tolerance.

The fourth of the above cited benefits to be gained from Quality Control makes a ready appeal to the inspection organisation. In so far as inspection effort can be distributed on a rational basis, such effort will be used to better economic advantage than where a system of Quality Control is lacking. At the same time the management may be reassured by the fact that no case is known of inspection costs having been increased as the result of introducing a Quality Control system.

The fifth mentioned advantage is probably the most vital of all. It marks the advancing viewpoint of manufacturing interests that are alive to the importance of product quality. And its general recognition is one of the paramount needs of industry at the present time. Fortunately, signs have not been lacking in authoritative quarters, during recent years, of a change in outlook towards the general quality problem that heralds a more widespread recognition of this need for rational and economic co-operation in inspection effort as between manufacturer and purchaser.

Quality-mindedness in the Machine Shop. After more than three years' experience in the application of Quality Control to machine-shop production the author has come to the conclusion that any manufacturing organisation seeking to obtain effective control over product quality must give a very great deal of consideration to the development of quality-mindedness among its factory personnel, and particularly among the machine-shop operatives. For it is this part of the organisation which exercises the most important single influence upon the quality of the manufactured product and upon the cost of attaining that quality.

Only too often, alas, is it the case that the management regard the general problem of quality, and the inspection necessary to maintain acceptable quality standards, as but another stumbling-block in the way of manufacturing the product at the desired cost and delivering it in the

scheduled time. This feeling usually develops because, when product is rejected by the inspection department, money must be spent on replacements or repairs, delivery of the product is delayed until the replacements or repairs are made and, finally, the earnings of the machine-shop operatives may suffer. Where this feeling is allowed to breed, a narrow view of such consequences of product rejection is inevitably created which can result in an incorrect factory attitude toward the quality problem.

Of course, the management should be aware that, in a broad sense, a constructive quality control programme is actually an aid to meeting delivery schedules, keeping to cost estimates, and yielding high earnings to the machine-shop operatives. Manifestly, the manufacturing problem is not so much one of making a given quantity of product at a given cost and within a given time; but rather, and primarily, one of making that product in accordance with certain quality restrictions. Hence the factory personnel must be made to realise at the outset that any product which fails to accord with the given quality restrictions is no more complete than if some physical items were actually missing from it. In this connection a production executive once remarked that there are two ways of getting no output: One is to make nothing, and the other to make defectives—and the former course is the less expensive of the two!

When translating these broad principles into the sphere of active Quality Control, the management must be on the alert to prevent any shift in responsibility for quality from the production departments to the inspection department. This misplacing of the onus for maintaining quality standards usually occurs in those cases where the inspection function has degenerated into the mere sorting-out of bad work from good, or where the inspectors actually make adjustments that should have been carried out by the producing organisation in the first place. *Under no circumstances must the inspection staff be allowed to become a quality prop for the factory.*

A powerful aid in promoting a correct factory attitude to the general quality problem is the use of quality incentives. A widely practised method of developing quality-mindedness among machine-shop operatives is to have defective work sorted or repaired by the operatives responsible in their own time. However, in formulating any plan embodying a quality incentive, it is better psychology to state the incentive as a bonus for good work rather than as a penalty for bad work. Unfortunately, the use of a bonus proportioned to the quality of the work is by no means as extensive in industry as the use of a bonus for higher output. It is the

author's belief that here there is a fertile field waiting to be tilled by industrial engineering effort. For there are many process operations wherein the manufacturing loss due to poor quality is of the same or even greater order of magnitude than the value of the labour required to perform the operation In this connection it is interesting to note that the advent of quality control methods and, in particular, of the control chart for fraction or number defective, has quite recently led to the development of quality bonus systems as a means of improving product quality.*

Finally, when considering the implications of such developments, one must bear in mind that the introduction of a rational and comprehensive system of Quality Control into any manufacturing concern, while in the first place a technical matter devolving mainly upon the inspection organisation, belongs ultimately to the domain of scientific management. The purely technical side of Quality Control—the use of statistical methods as the basis of inspection routine, in other words—should not be regarded as the sole means of attaining high quality standards, although it is unquestionably the most important. The manufacturing organisation as a whole must become permeated by that atmosphere of quality-mindedness without which the maximum benefits from Quality Control cannot be obtained.

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* *Industry Illustrated,* March, 1943, p 24; and *Electrical Review,* 22nd October, 1943, p. 536 (See also Chapter VI.)

CHAPTER II

WHAT IS QUALITY CONTROL? WHAT ARE ITS ADVANTAGES?

QUALITY Control, that is to say, the statistical control of the quality of a product during the actual course of manufacture, is essentially an inspection technique. Moreover, it is a technique involving the inspection of production processes, rather than of manufactured products. Perhaps the best definition of the quality control method is that *it puts patrol inspection on a sound basis.* In doing so it ensures that the maximum of directly useful information is correctly obtained about the way in which the production process is behaving, and that this information is gained with a minimum of inspection effort. In the words of the Select Committee on National Expenditure, in its report on the Royal Ordnance Factories*: "Statistical methods in the control of manufacture . . . yield information which assists the producer to discover the causes of defects and even to anticipate their occurrence, with resulting benefit to output."

Systematic Patrol Inspection. When developing a routine method of machine-shop inspection capable of working in harmony with modern production methods the main objective must be *to establish control of product quality at all stages of manufacture.* To carry out an operation, or a sequence of operations, on a batch of components and then to rely on subsequent inspection to eliminate components that are faulty, does not meet the case. Close watch by inspection during actual operation on the components, although somewhat nearer the mark, also fails to meet the basic requirement of Quality Control unless it discovers in the operation a tendency towards defective production before defective work has been produced In plain language this means that patrol inspection, i.e., inspection of components during actual production, must have such a grip on the situation as to reduce the production of defective components to a negligible minimum, and be in a position to guarantee that batches of components reaching the assembly departments will be usable except for a percentage so small as to be of no account.

It has to be admitted that this is aiming high. But Quality Control in our sense of the term can have no other meaning. Any compromise will simply leave us where we are. The usual inspection procedure in the average engineering works provides for a certain amount of inspection

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* Eleventh Report, Session 1941-42 (published by H.M. Stationery Office on 16th July, 1942).

supervision during actual operation on the components, but relies mainly on some form of batch inspection after the operation (or sequence of operations) has been completed, to weed out unserviceable components from the batch. This, however, and as has been previously stated, really means that satisfactory components are selected, or unsatisfactory components weeded out, *after manufacturing time has been spent on them.* With production operations carried out under controlled conditions, on the other hand, action is taken to prevent the manufacture of defective components by the interception of any tendency in the operations to swing outside predetermined tolerances at a sufficiently early stage in this outward swing *to arrest the actual production of unusable parts.* This brings us right to the heart of Quality Control as an applied function of inspection It does not mean for a moment that inspection, or the need for it, may be dispensed with. But it does mean that inspection is more effective and more far-reaching when it controls productive effort in the quality sense, instead of measuring the quality of the product after manufacturing effort has been expended upon it.

The routine application of quality control technique to production processes centres upon the so-called quality control chart which is, in effect, a continuous graphical record of product quality As will be explained in the next chapter, the control chart provides a visual means of segregating variations in product quality that can safely be left to chance from those which cannot be allowed so to continue. By plotting the successive findings of process inspection on such a chart, the presence of these latter " assignable " causes of variation is immediately revealed, so that corrective action can be taken to eliminate them before defective product is turned out by the process. In the course of time, as these assignable causes of quality variation are progressively eliminated, the production process is brought completely under control and eventually yields a stable product, that is to say, a product whose variations in quality are entirely of a random nature. When this goal of Quality Control is attained, it is possible to predict in advance what percentage of *future* product will lie within any specified pair of limits. This unique feature of the quality control method is in sharp contrast to traditional inspection practice, where the percentage falling within given limits can only be ascertained by 100 per cent. inspection of *past* product.

From the point of view of inspection routine there are three main operational principles which are fundamental to Quality Control:

(1) By focusing attention on the *pattern* of the observed results of inspection, rather than upon the number of defective items produced one

is able safely to judge the quality of the mass of product submitted for inspection by examining relatively small samples instead of all items in the mass. (*Sampling Inspection.*)

(2) By analysing the measured results of sampling inspection and by promptly studying the pattern of these measurements, one is able to take such preventive action as will remove trouble-making causes *before* defective items are actually produced. (*Control Chart for Measurements.*)

(3) By analysing the number or fraction of defective items found during manufacture, in cases where measurement is either inapplicable (e.g., visual inspection, internal screw threads) or else uneconomic (e.g., fast production and multi-dimensional checking by limit gauges), one is able to take such preventive action as will remove causes making for an increased rate in the production of defective items. (*Control Chart for Defectives.*)

The principle of sampling inspection is basic and applies not only to the quality control of production processes, but also to the quality determination of the resulting product. This latter use of sampling inspection procedures in the quality assessment of finished or semi-finished bulk products is of cardinal importance to-day in that it leads to considerable economies in overall inspection effort and therewith to a corresponding saving in man-power.* Suffice it to mention here that it is a subject which during the later war years excited the attention of official inspecting bodies such as the A.I.D. and the C.I.A. This is only natural since, according to the Ministry of Production, one-half the total manufacturing effort of this country was directed to making components (i.e., intermediate products for assembly elsewhere to form completed munitions of war).

Quality Control, then, involves sampling inspection of the product *during* manufacture. In the familiar terminology of the machine shop this means a *planned system* of patrol inspection of the production process in which a fixed number of piece parts is examined by the patrol inspector at each visit to the machine. That fixed number is known as the " sample size " and varies from 2 to 10 in the case of Quality Control by measurement, and from 5 to 20 or more in the case of Quality Control by counting defectives. The amount of inspection effort given to the production process, that is, the percentage of the product inspected during manufacture, may be altered at will by varying the inspection interval. For

* *Cf.* H. Rissik: " Quality Assurance through Sampling Inspection," *Engineering Inspection*, 1943, Vol. 8, No. 2, pp. 12-24.

example, if the production rate is 100 per hour and the sample size is fixed at 5 parts, then a half-hourly inspection interval will ensure that 10 per cent. of the product is examined. This might be a reasonable proportion to start with, for control chart purposes. As soon as the chart begins to show evidence of process stability, the amount of inspection may be reduced by increasing the interval between patrol visits to, say, 1 hour (5 per cent.) or even 2 hours ($2\frac{1}{2}$ per cent.) if control is successfully maintained.

The point to note here is that subsequent 100 per cent. inspection can be, and in fact will be, dispensed with under these conditions The proof of this is perhaps best given by citing a specific instance—only one among many similar cases reported by different firms—where two successive batches of piece parts turned out by an auto were subsequently detail inspected. The first batch of some 10,000 items was subjected to the prevailing (and customary) casual patrol inspection coupled with periodic attention by the tool-setter. When the batch was completed and examined in detail 765 defective piece parts were found. The next batch of about 7,000 piece parts, produced under identical machine-shop conditions, and on the same machine, with the same tool-setter in charge, was subjected to a quality-control routine. That is to say, patrol inspection was systematic *and the results were plotted on a control chart*. Moreover, action was taken where indicated by the chart—the machine was stopped and the tool-setter instructed to re-set. When this batch was completed it was found to contain only 9 defective piece parts.

Another and rather more spectacular example of this procedure known to the author is the case of a precision engineering firm in the North London area which after January, 1943, was passing out " quality controlled " components direct (i e., without any subsequent inspection) to the I.N.O. authorities at the rate of over 100,000 per week.

The Quality Control Chart. Fundamentally, the problem of Quality Control is one of controlling variability in some directly measurable quality characteristic, e.g., piece part dimension. tensile strength, hardness, weight ; or, alternatively, the fraction of defective articles produced by a repetitive manufacturing process. In practice this is effected by analysing the observed variability and comparing it with an objective standard. Fortunately for the engineer, the statistician has provided him with such a standard of variability, namely, the yardstick of random variation, defined by the so-called Normal Distribution Law underlying a stable production process. Thus, provided we have evidence of process stability, we are able to specify certain limits within which practically all observed

values of the variable quality characteristics are expected to lie, and will lie in the long run. For example, if a series of measurements on a succession of piece parts, produced supposedly under the same essential conditions, are found to give dimensional values lying outside these limits, then we may safely infer that they were not, in fact, so produced. In other words, we are forced to the conclusion that the production process was not stable in the first place. Under these circumstances, *but not otherwise*, the engineer is justified in looking for assignable causes of variation in his production processes. Although the variations in the observed values of the quality characteristic may, on the whole, appear to be of a purely random nature, the production engineer has no means of satisfying himself on this vital point, except he resort to the statistical method of analysis implicit in quality control technique.

This consideration brings us to the very heart of Quality Control as a routine method enabling preventive action to be taken *before* trouble develops, instead of curative action *after* the trouble has arisen. As already mentioned, the basis of the quality control method is the control chart which is, in effect, a continuous graphical record of product quality. From the standpoint of practical application in the machine shop it has the supreme merit of simplicity. Experience has shown it to be a powerful means of stimulating production personnel, including both operators and tool-setters, to turn out good work. In this connection it lends itself, in one form at least, to the institution of quality bonus schemes for manual or semi-automatic process operations. Furthermore, the actual construction of quality control charts involves only the simplest arithmetic and is based on formulae derived from the statistical approach to industrial problems whose reliability has been proved in the practical field for nearly a quarter of a century.

The fundamental principles underlying the use of the quality control chart are conveniently summarised in Fig. 1. This diagram serves to demonstrate, in quite general terms, how the control chart functions as a means of assisting the production engineer to improve the efficiency of his manufacturing processes. Without resort to statistical technique he can at best obtain only a *manufacturing control* of his processes, by trial and error methods founded on engineering knowledge allied with experience and, possibly, intuition. Traditional practice enables him to plot quality observations on a chart embodying only the given engineering tolerance limits, E_1 and E_2, that specify the permissible range within which the product will give satisfactory technical performance. In this way he can keep a running check on the quality of his output and, if there were

no reason connected with quality assurance or economy for going beyond such a concept of " go " and " not go " tolerance limits, statistical theory would have nothing to add. His quality chart, basing itself on these limits, then merely serves as a gauge for product *already made*. If, now and again, the quality values fall outside the limits E_1 and E_2, the production engineer will from time to time have to take action with a view to locating and removing the source of trouble. *On each such occasion, however, he is landed with defective product.* On the other hand, if the quality values remain inside the limits E_1 and E_2 he may wish to reduce the tolerance range so as to obtain a greater efficiency in design or piece part assembly. But on what basis is he to establish narrower tolerance limits ?

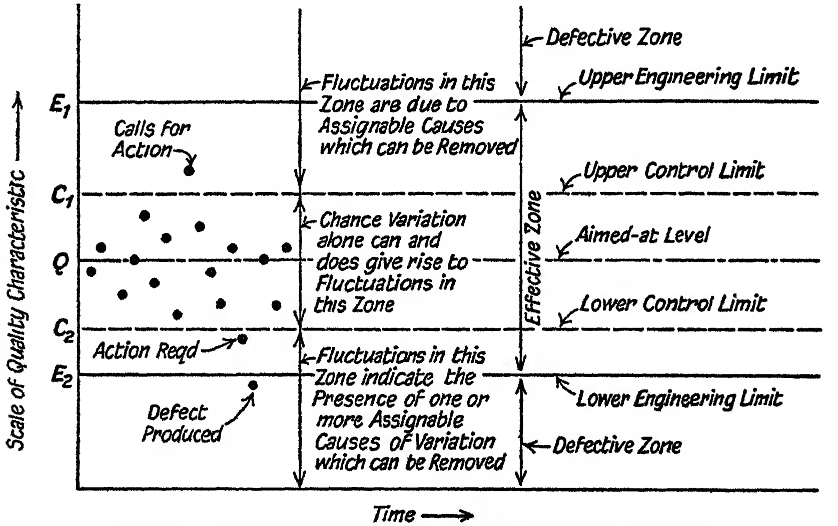

Fig. 1. ELEMENTS OF THE QUALITY CONTROL CHART

In contrast to the foregoing practice there is the possibility of achieving *statistical control* of a production process. By the use of a simple arithmetical procedure the production engineer can specify a level of quality Q at which to aim, together with two control limits, C_1 and C_2, which serve as a quality gauge for product *not yet made.* A quality chart incorporating such limits enables him to be on the look-out for causes of quality variation that need not be left to chance—for assignable causes, in other words—without his being landed with defective product whenever and immediately the chart indicates that one or more such causes are at work in the production process. His chart thus becomes a *control* chart,

in which the function of the limits C_1 and C_2 is, to quote Shewhart, "to call attention to evidence for believing that the manufacturing process includes assignable causes of variation in quality which may give trouble in the future if they are not found and removed"

How Quality Control Benefits Production. The chief claim of Quality Control to rank as a systematic aid to production is thus its ability to anticipate faulty manufacture and thereby to point the way towards corrective action before defective work is actually produced. This claim, moreover, is no longer in dispute. There is enough evidence available to-day from a variety of production engineering organisations to convince even the most sceptical traditionalist that a system of Quality Control does in fact minimise defective production. A few typical examples should therefore suffice to indicate the order of magnitude of the savings that arise from the introduction of Quality Control into the machine shop.

Table I shows the results recently achieved in the case of a certain line of product turned out by a large electrical equipment manufacturer in the Central England area. The figures given in the first line of the table are averages for 21 weeks prior to the introduction of Quality Control, while those in the second line of the table are the corresponding averages for 11 weeks after Quality Control was introduced In reporting these results the firm in question pointed out that no change whatever had been

TABLE I

QUALITY CONTROL RESULTS WITH CONTINUOUS PRODUCTION

FIRM Electrical Equipment Manufacturer	Average Weekly Gross Output		Product Finally Accepted		Product Rejected	
	No.	%	No.	%	No.	%
Before Quality Control.	13053	100 0	11143	85·4	1910	14·6
After Quality Control	14381	110·2	13545	94·2	836	5·8
Difference . .	+1328	+10·2	+2402	+8·8	−1074	−8·8
Percentage Change .	+10 2	+10·2	+21·6	+10·3	−56 3	−60·2

made in the manufacture other than its subjection to a system of Quality Control. Hence the 10 per cent. increase in average weekly *gross output* must be attributed to the effect of Quality Control on production, as distinct from its effect on the product (60 per cent. fewer rejections). The report also explained that as a further result of the application of Quality

Control in this case, a 30 per cent. reduction in inspection effort had been achieved. The amount of final (100 per cent.) inspection of the product fell from 5 to 2½ man-hours per 1,000, against which had to be set off an additional 1 man-hour per 1,000 for inspection under the system of Quality Control

A similar case, although different in character from the production standpoint, is that shown in Table II which refers to successive batches of a very troublesome component of a complicated electro-mechanical assembly, one of several manufactured in considerable quantity by a precision engineering firm in the London area. This particular component, a main casting of aluminium alloy, undergoes 18 successive machining operations before reaching the assembly line. Of these operations 11 were subjected to the quality control routine which was later standardised throughout the machine shop.*

TABLE II

QUALITY CONTROL RESULTS WITH BATCH PRODUCTION

FIRM : Precision Engineering	Batch Quantity		Initially Accepted at Detail Inspection		Finally Accepted after Rectification		Rejected as Scrap	
	No	%	No.	%	No	%	No	%
Before Quality Control	450	100	224	49 8	150	33·3	76	16 9
After 11/18 Q C	500	100	390	78 0	65	13·0	45	9·0
Difference	—	—	—	+28·2	—	−20·3	—	−7 9
Percentage Change	—	—	—	+56 6	—	−60·9	—	−46·8

The effect of Quality Control in this case was to reduce the proportion of rejected but repairable product by 61 per cent. and the proportion of finally rejected product by 47 per cent., with a corresponding gain of 57 per cent. in initially satisfactory product. The experiences of this particular engineering firm since the introduction of Quality Control as a routine machine-shop procedure have already been related in detail elsewhere,† but Fig. 2 summarises the operating results obtained over a period of six months soon after the Quality Control system came into force. The curves express the labour time spent on producing scrap

**Journal of the Institute of Engineering Inspection*, Vol. 7, No. 1, Jan.-March, 1942, pp. 4-19 ; also *Industry Illustrated*, Vol. 10, No. 3, March, 1942, pp. 8-19.

† *Machinery*, Vol. 61, 1942, pp. 118 and 169-172.

and in rectifying defective piece parts as a percentage of the machine-shop or section output in man-hours. (It should be mentioned here that during the period surveyed in Fig. 2 the machine-shop production figures rose by over 25 per cent. Furthermore, Quality Control did not apply to all sections of the machine-shop, nor to more than a fraction of the aggregate process operations.) Some idea of the difficulties in the way of a quality-control programme in this case can be gained from the fact that the machine shop deals annually with some 12,000 separate components, each of which undergoes on the average over five distinct machining operations

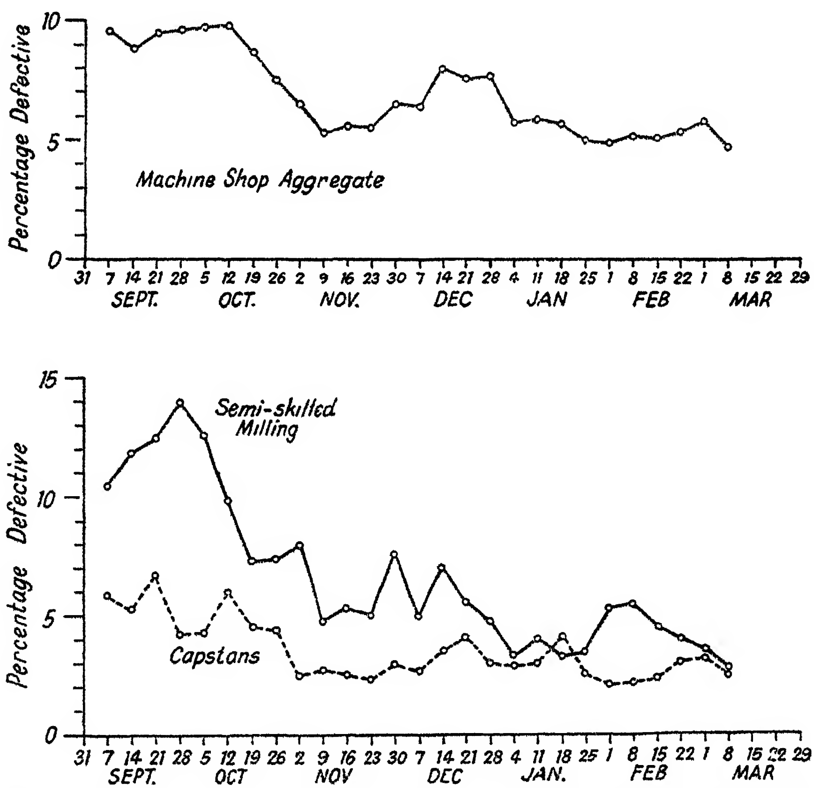

Fig. 2. Influence of Quality Control on Machine-shop Production

Another example, given by a large engineering concern in the Manchester area, is that of the application of Quality Control to the mass production of rivets manufactured on a Petermann No. 1 Automatic

and machined to a tolerance of 0·001 in. Prior to the introduction of the new system the process was subjected to casual patrol inspection, and the product was finally inspected 100 per cent. Since Quality Control was introduced the final inspection has been eliminated entirely, leading to a saving of 20 man-hours per week on a production in the region of 6,000 weekly. The firm reported that at the same time the number of rejections had been reduced from 13 per cent. to less than 5 per cent. of the total output. Similar results have been reported from a firm in North London engaged on component production. Quality Control was introduced in the auto section, comprising a battery of multi-spindle Conomatic, Gridley and Churchill machines. In consequence, not only was a better product being obtained, but also some twenty inspectors, hitherto engaged on 100 per cent. inspection of the machine output, were released and put on to productive work. At the same time the quality control charts revealed characteristic differences in performance between the various machines ; information that proved invaluable to the planning department in arranging its production schedules.

Another well-known engineering firm in the Midlands, also engaged on component production, and using multi-spindle automatics, reported that " there is a noticeable increase in effective output when once the tool-setters concerned have appreciated the evidence provided by the quality control charts . . . due to this rise in effective output, shop efficiency is higher and setters' and operators' earnings have been increased." In this connection the author knows of several instances where, after the experimental application of Quality Control to certain machine-shop processes, the production staff have actually made a request to the chief inspector that specific jobs be subjected to Quality Control.

Finally, the experiences of the Bristol Aeroplane Company—about which we shall have more to say later—deserve mention. The Aircraft Division of this manufacturing organisation had for some time past been using dot diagrams, similar in appearance to quality control charts, as a means of recording and analysing the speed and performance of production aircraft. In October, 1942, the decision was made to apply the statistical method of Quality Control, for an experimental period, to the automatic section of the machine shop. Accordingly a training school was set up to instruct women inspectors in the routine application of Quality Control, these inspectors having been previously employed on final inspection of machine details. The experience gained in the automatic section has been sufficient to convince the management of the value

of a quality control system, and the training facilities have accordingly been extended with a view to enlarging the scope of the system so as to embrace the remainder of the machine shop. Mr. H. J. Pollard, Manager of the Aircraft Division, to whom the author is indebted for permission to publish this information, reported early in 1943 that " the extension of the quality control system to cover most sections of the machine shop (with the probable exception of the centre lathe section) is now in progress " He went on to to say that, " to date, the particular features noted are a general improvement in the standard of production, together with a substantial drop in rejections and scrap. It is, therefore, intended to introduce quality control methods, amended as necessary, to such departments as the press shop and other detail producing shops."

Quality Control as a Machine-shop Aid. The principal benefits of a system of quality control are, then, as follows —

(1) improved product quality

(2) reduced process inspection ;

(3) smoother production flow.

These are clearly important advantages. But there are a number of other advantages, of a more indirect character perhaps, which accrue to the user of quality control methods in the machine shop. It is by now a common experience that the introduction of control charts, and their interpretation by production personnel, has led to a better, more objective understanding of the capabilities and limitations of machine tools in everyday use. Moreover, it is found that control charts, when posted on or adjacent to the machines to which they relate, add a new interest to the operator's job. In some cases such charts have even been used as a basis for monetary incentives directed towards improving quality.

It is somewhat difficult to describe all these secondary benefits of Quality Control in concrete terms But a few examples quoted from the author's experience may help to convey a picture of Quality Control as an aid to machine-shop production.

Here is what a machine-shop superintendent had to say after about a fortnight's experimenting with Quality Control on one or two troublesome production processes :—" High spots that have come to light are as follows—

(*a*) Defective production is not always the operator's or tool-setter's fault. The machine usually needs some overhaul to do the job properly.

(*b*) The system informs us when the tool needs regrinding much earlier than a practical man would know it.

(c) Operator's fatigue or indifference is shown up.

(d) A target for tool-setting is automatically provided and stimulates interest in tool-setting that did not exist before.

(e) Both tool-setters and operators become interested in the results if shown on charts that are displayed near the machine"

A friend of the author's, an official responsible during the war for installing quality control systems throughout Royal Ordnance Factories up and down the country, summarised the reaction of machine-shop personnel to the introduction of Quality Control as follows:—

"The inspector gets a better product. His or her work is much more interesting and gives the inspector an increased sense of importance. The following comments by girl inspectors working under a quality control system confirm this view—

(1) They find inspection under Quality Control more interesting than the patrol gauging to which they were hitherto accustomed.

(2) They feel that they have something to show for their day's work.

(3) They are quite definite that it is a better system of inspection.

(4) They appreciate that their control charts will help to prevent rejects.

"As far as the shop foremen and tool-setters are concerned, the great benefit of Quality Control is that it gives them a remarkable sense of increased mastery over their job. They are provided with a concrete basis for running their work to the best advantage."

As a last example we shall cite an official report by the Deputy Works Manager of S. Smith & Sons (Motor Accessories) Ltd., on the introduction of quality control methods into their Cricklewood factory towards the end of 1942, after the author had given a series of lectures on the subject to their production and inspection personnel. Part of this report we quote with his permission:—

". . . . . . . the mechanical troubles were overcome one by one and their elimination could be traced in the control charts.

"The foreman of this machine shop, at first, was sceptical of any value which Quality Control might have, but he is now convinced that it is of definite value to him and he is anxious that the use of this system shall be extended to cover the whole of his machine shop. In his words, 'the production of components from these machines is smoother.' The setter does not have to worry over the condition of his machine but is guided by the plotted points on the charts, and he is able to estimate when tools will require regrinding, and when adjustments are required to the machine bearings or slides. The result is that machines are re-set before serious

trouble has developed and the work moves directly away from the machine to subsequent operations without further inspection . . . .

" A capstan machine producing a small brass bush was made the subject of a complaint by the section inspector who maintained that the component was not being produced to drawing sizes. An investigation with the aid of quality control charts proved beyond doubt that a number of brass bushes were being produced outside specification tolerances, but that the machine was incapable of producing this particular part to the required tolerance. Approach was made to the Engineering Department with a view to increasing the tolerance. This step was approved and an increased tolerance was added to the drawing.

" The value of Quality Control to the Company in this instance was twofold. The foreman was convinced that the machine was not producing work to specification, without long argumentative efforts from the inspector, and he, therefore, started his investigation sooner than usual. The increased tolerance has allowed the machine to run for a longer period without stoppages. In other words, economy was effected in two directions, supervisory time and machine time.

" It is worth while, I think, to put on record that though the supervisory efforts of the machine shop are generally very conservative in their methods, in every section where Quality Control has been demonstrated the foreman has asked that it should be applied more extensively."

CHAPTER III

THE BASIC PRINCIPLES OF QUALITY CONTROL

In that wide area of technology which we commonly term engineering, and which may be defined as the technique of wringing material benefits from a recalcitrant nature by the intelligent use of mechanical tools, man's control over the quality of his artifacts has been for centuries perforce a matter of personal skill aided by artistic judgment. In all creative art having a technological character, whether architecture, bridge building or the construction of mechanisms (to cite obvious examples), the criterion of quality is ultimately the fitness of the object created to the purpose it subserves. Both these statements may be summed up in one word—craftsmanship. It is, therefore, not surprising to find that technological development was, until comparatively recent times, completely in the hands of the craftsman.

Craftsmanship and Quantity Production. While it is common knowledge that the coming of the Industrial Revolution in the eighteenth century heralded the doom of craftsmanship in the technological sphere, it is not generally realised that the actual death-blow was delayed until the end of the following century, when the principle of interchangeability of component parts finally succeeded in revolutionising our concept of product quality. The application of this revolutionary technological principle, which underlies the repetitive manufacturing process that characterises modern production engineering, was originally bound up with the idea of exactness—a legacy from Newtonian mechanics—which then held sway in the realm of science. As a result, attempts were first of all made to produce interchangeable piece parts to exact dimensions, but experience eventually showed this to be impracticable and indicated the necessity for some degree of tolerance in the manufacture of such piece parts. About 1840 a single tolerance limit based on the use of a "go" gauge was introduced, followed some thirty years later by twin tolerance limits set by means of "go" and "not go" gauges.

Since about 1870, then, the traditional practice of quality supervision in production engineering has been one based on the actual tolerance limits adopted in manufacture. Under these conditions the quality of the product is defined by the degree in which a succession of piece parts, whether in one or more batches, or in a continuous output for a day or a week or other period, falls within the specified limit of tolerance. Any piece part whose dimensions fall outside the appropriate tolerance ranges

laid down by the designer will presumably not fulfil its function and is accordingly classed as "defective." The quality of any succession of piece parts yielded by a given machine-shop process is consequently measured by the proportion of defective parts in the total produced. The lower this proportion, the better is the quality of the product.

Any rational system of quality control must, therefore, take into account the fact that no repetitive manufacturing process can or will produce articles that are exactly alike. A certain amount of variability or non-uniformity is inevitable in the case of products manufactured on a quantity basis. The degree of variability encountered in any particular instance depends, however, upon the precision of the manufacturing process. In devising a technique of quality control in harmony with modern quantity production methods we must therefore start from the premise that, given a quality criterion specified in terms of a pair of manufacturing limits, the question whether any particular piece part will meet the criterion or not—whether it will be "effective" or "defective," in other words—is settled by the variability *inherent in the production process.* If the degree of uniformity in the process is inherently high, that is to say, if there is very little variation from one piece part to the next, the likelihood is that the criterion will be met; the dimensions of the piece part will generally fall within the specified manufacturing limits and the part will thus be effective. On the other hand, if the degree of uniformity inherent in the production process is low, so that piece parts vary considerably from one to another, it is quite likely that some piece parts may fail to meet the specified quality criterion and so become defective.

Causes of Quality Variation. The first essential, then, of a rational method of achieving positive control of product quality is a determination of the variability inherent in each stage of the manufacturing process, that is, in what we may term each process operation. To this end measurements must be taken in accordance with some pre-arranged plan—hence the need for keeping process inspection records. Such data constitute the raw material for the quality control engineer (or the quality control section of the inspection organisation) to work upon.

The second requirement, which follows logically from the first, is a scientific means of analysing such data with a view to resolving the inherent variability of the production process into its two basic components, viz. :—

(1) that due to the operation of forces working at random (i.e., to *chance* causes);

(2) that due to the operation of forces working consistently in some particular direction (i.e., to *assignable* causes)

The purely random variation represented by the first of the above components is termed "non-significant," for it is one that merits no investigation; it arises from what is known as a constant system of chance causes, and no amount of engineering effort (short of a complete change in the production process) can have the slightest influence upon such a system.* In short, it represents the rock bottom of variability inherent in the process. The non-random variations comprising the second of the two components are termed "significant," for they signify the presence within the production process of an assignable cause of variability whose operation, if allowed to continue unchecked, will sooner or later give rise to defective product.

A repetitive production process yielding piece parts whose dimensions are subject only to random variation is one which is commonly termed *stable*.† Conversely, if assignable causes of variation are at work within the production process as well as chance causes, the process is referred to as *unstable*. The segregation of these two fundamental types of causes, upon which any rational system of quality control depends, is a statistical problem of a relatively simple character whose solution can readily be made part and parcel of process inspection routine On the other hand, the recognition and elimination of an assignable cause of product variability, once its presence has been indicated by statistical technique, is essentially an engineering problem whose solution calls for a general knowledge of modern production methods together with some experience in the diagnosis of production troubles.

Dimensional Variation and Defective Production. In the sphere of production engineering, the most important quality of the product is dimensional in character, that is to say, one quality criterion is expressed in terms of an upper and a lower dimensional limit—the so-called tolerance or engineering limits. There are, of course, other quality characteristics with which we may have to be concerned and which cannot be specified in this way, e.g , colour, finish, the presence or absence

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* *Cf.* H. Rissik: "Statistical Methods in Engineering Practice—I. Fundamental Aspects of Statistical Technique," *The Engineer*, 1940, Vol 170, p. 341.

† W. A. Shewhart, to whom the development of quality control technique is due, has defined such a process as being "in a state of statistical control." To distinguish this *state* from the *operation* of statistical control which is, in general, necessary to achieve it, E. S. Pearson in *B S S.* 600-1935 has suggested the alternative term *statistically uniform.* In the experience of the author, the shorter and succinct term *stable* has proved more acceptable to engineers.

of some kind of defect. But for the moment let us consider the question of defective production only in terms of whether or not an individual piece part fails to comply with the dimensional requirements laid down by the design department.

Under these circumstances the production of defective piece parts may arise from any one or a combination of the following causes :—

(1) Errors in operation (e.g , misreading of a drawing, careless handling of a machine, faulty machine loading, etc).
(2) Faulty tool-setting.
(3) Difficulties imposed by design (e.g , engineering limits too narrow).
(4) Poor tooling.
(5) Faulty material
(6) Inadequate machine maintenance.

Clearly these causes of dimensional variation making for defective production are not all of the same kind. Some are inherent in the production process, whilst others are external to it. Of the former, (3) is fundamental and (6) is contributory. The working tolerance should be big enough to take into account (*a*) the inherent precision of the process, and (*b*) a reasonable deterioration in this precision due to machine wear. In other words, *the working limits for the dimension produced should allow fully for the chance causes of variation* which underlie (3) and (6). Because it is these causes, and these causes alone, which determine the "stability limits" or natural tolerance of the production process, that is to say, the minimum overall dimensional variation of which the process is capable.

What about the assignable causes of dimensional variation ? These are, by definition, those which can be assigned to some specific physical element in the production process. Hence they include such causes of defective production as (1), (2), (4) and (5), which are all of them external to the production process as such. Strictly speaking, (6) is also an assignable cause ; because by proper maintenance the precision of the process can be kept more or less indefinitely at the initial level. But (3) is definitely a question of chance causes ; because it rests upon the rock bottom of dimensional variation inherent in the production process *This concept of a basic random variation is the key to the quality control method.*

What does a production process look like when it is shorn of its unstable superstructure of systematic variation and reveals only the solid bedrock of random variation ? Can we make a simple picture of such a *stable* production process ? Consider, by way of an actual example,

an auto parting off round bar to a nominal length of, say, 1·125 in. Suppose we know in advance that the limits of accuracy for this particular machine under these conditions are represented by a dimensional tolerance of $\pm 0{\cdot}001$ in. In other words, we do not expect any piece part to be shorter than 1·124 in. or longer than 1·126 in. Is there any way in which we can describe the behaviour of our production process in terms of the dimensional variation taking place between the known limits of $1{\cdot}125 \pm 0{\cdot}001$ in.?

The Dimensional Pattern of Quality Control. When viewing such a production process from the standpoint of Quality Control we must learn to look, not for the individual piece part dimension, but for the dimensional *pattern* of the piece parts produced. This is, after all, only commonsense. Because in "mass production" we are really interested in the mass of the product, not in the individual items that make up the mass. What then is the dimensional pattern of our ideal auto turning out large quantities of piece parts to a nominal length of 1·125 in. and with an assumed accuracy of $\pm 0{\cdot}001$ in.? The answer to this fundamental question is provided by Fig. 3.

We shall assume by way of illustration that a patrol inspector visits the machine, say, once in six minutes, picking up the piece part as it drops into the hopper and then measuring its length with a micrometer or comparator accurate to 0·0001 in., i.e., one-tenth of a "thou." After an hour he will have collected a sample of ten piece parts whose individual dimensions might be :—

1·1249	1·1250	1·1245	1·1249	1·1251
1·1250	1·1253	1·1251	1·1249	1·1250

These ten dimensions are shown as dots in the top diagram of Fig. 3, against the number 10 in the column headed "size of sample." After another hour our patrol inspector will have collected a further ten piece parts whose individual lengths might be :—

1·1250	1·1243	1·1249	1·1252	1·1252
1·1251	1·1255	1·1256	1·1252	1·1255

On adding these further ten dimensions to our original dot diagram, we obtain the result shown in the second diagram of Fig. 3, against the "sample size" $n = 20$. The dimensional pattern we are seeking is beginning to show itself. So far the maximum number of piece parts having a particular dimension, say, 1·1249 in., is four. The number clearly gets less the further we depart from the aimed-at value 1·1250 in.

After five hours our patrol inspector will have a sample of 50 piece parts, whose individual dimensions follow the pattern shown in the

third diagram of Fig. 3. Here we have abandoned the use of dots in favour of "bricks" to represent the piece parts. For example, the column standing on the scale number 51 is built up of eight separate bricks. This indicates that 8 out of the 50 piece parts so far collected have a length of 1·1251 in. We can say that in our dimensional pattern the particular dimension of 1·1251 in. occurs with a frequency of 8 times in 50, or 16 per cent. of the time, as indicated by the column in Fig. 3

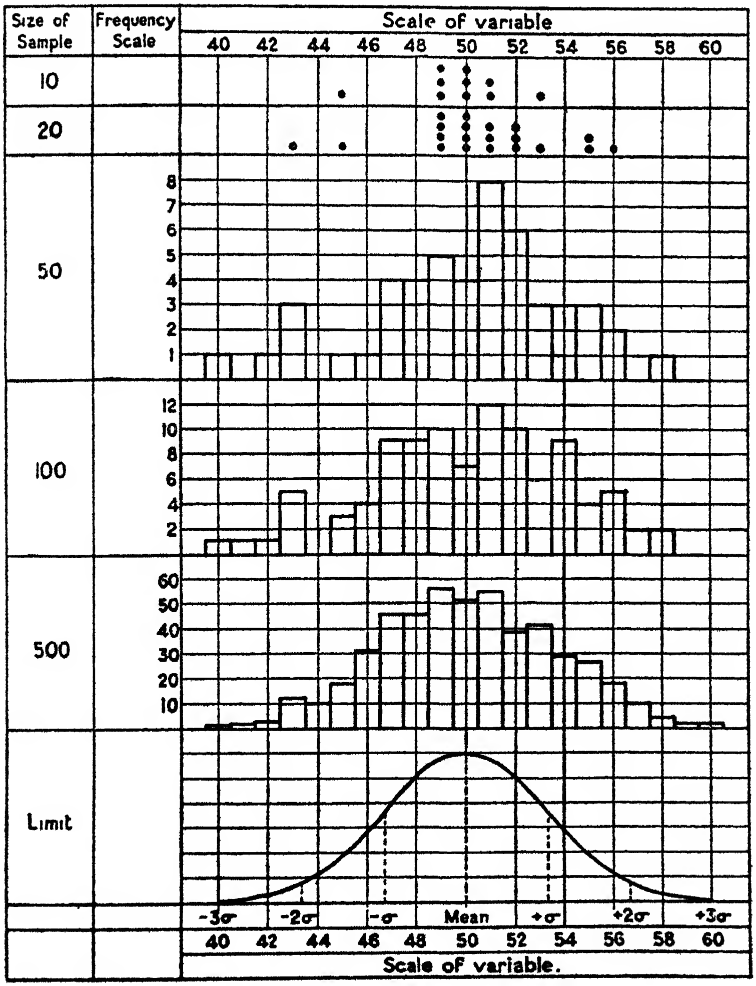


Fig. 3. THE PRODUCTION CHARACTERISTIC

headed "frequency scale." It will be seen also that the dimension of one of the 50 piece parts is on the bottom limit, viz., 1 1240 in. The fourth and fifth diagrams of Fig. 3 show the inspection results after 10 and 50 hours' production respectively (i.e , at the end of a shift and at the end of a week). The dimensional pattern is now quite clear. It is regular and very nearly symmetrical about the aimed-at value, the nominal dimension 1·1250 in Moreover, all the 500 piece parts fall inside the assumed working tolerance of $\pm$ 0·0010 in.

These five diagrams go to show that under the more or less ideal conditions of stable production, in which only random variation is present, there exists a quite definite and characteristic relation between particular dimensions and the relative frequencies with which they occur. This relation underlying our dimensional pattern is known as the Normal Law (of random variation) According to this law—whose mathematical derivation need not concern us in the least—the larger the size of the sample, that is to say, the greater the number of piece parts collected from our production process, the more regular does the dimensional pattern become and the more closely does it approach towards a smooth curve. In the limit, when the number of piece parts is assumed to be infinite, our dimensional pattern becomes the bell-shaped curve shown in the bottom diagram of Fig. 3.

In the language of Quality Control, a dimensional pattern such as the one we have been talking about is known as a *production characteristic** and in practice is represented by the bell-shaped curve of Fig. 3. This is an extremely important curve, and we must get to know a little about it if we are to gain any real understanding of quality control procedure. The outstanding feature of this curve is that it has been found to remain remarkably constant in both size and shape over long periods of stable production of a given job from a given machine. Provided production remains stable, that is, providing nothing unusual happens to the production process, we could go on measuring, day in and day out, large numbers of piece parts from the same machine, and we would always find that they fell into the same dimensional pattern represented by this bell-shaped curve. In other words, the curve is a characteristic feature of that particular machine performing that particular production operation. It is intimately bound up with the precision of the machine, the accuracy of the tool-setter and the skill of the operator, and it does not alter as long as that precision, accuracy and skill remain unchanged. Our

* The statistician calls it a "frequency distribution."

bell-shaped curve is, in fact, the "production characteristic" of that machine, job and operator.

The Production Characteristic as a "Percentage Defective" Indicator. As an illustration of the way in which a stable production process does in practice tend to conform to our ideal bell-shaped production characteristic, Fig. 4 shows the dimensional pattern observed in the case of 2,000 piece parts produced by a well-maintained modern auto working to a specified tolerance of $\pm 0{\cdot}001$ in. In this diagram, as in the middle three diagrams of Fig. 3, the height of each step gives the number (left-hand scale) or percentage (right-hand scale) of piece parts having the

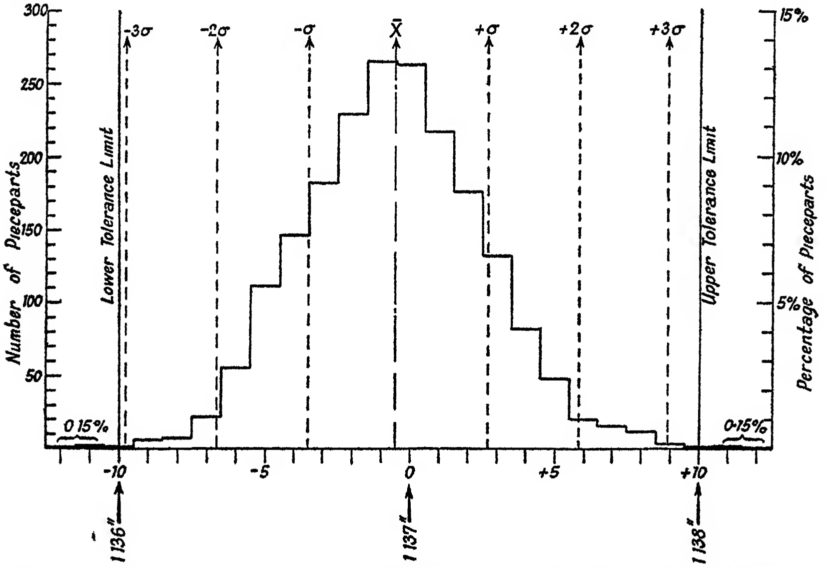


FIG. 4. ACTUAL PRODUCTION CHARACTERISTIC OF A MODERN AUTOMATIC LATHE

dimension given at the bottom of the diagram. It is possible, by simple arithmetical methods which need not concern us here*, to calculate, from the 2,000 individual measurements represented by Fig. 4, the production characteristic underlying this particular machine and operation. The result is shown in Fig. 5.

* These methods have been devised by the statistician, and to discuss them would take us outside the territory of Quality Control into the realm of industrial statistics. Engineers interested in such theoretical questions may refer to the author's article entitled "Probability Graph Paper and its Engineering Applications," published in *The Engineer*, 24th and 31st October, 1941. See also the *A.S.T.M. Manual on Presentation of Data*, obtainable through the British Standards Institution, 28, Victoria Street, London, S.W.1.

It will be obvious, from what we have already said about this bell-shaped curve, that a knowledge of its shape and size is a valuable piece of information about the production process to which it refers. In fact, we have in it a complete and concise picture of the kind of job inevitably produced by this process unless some change, some "assignable cause" of variation is introduced. From the production standpoint the most important use to which we can put this graphic picture is to estimate from it the percentage of rejects turned out by the process under different conditions. How this is done may be explained by reference to Fig. 5. Diagram (*a*) shows the production characteristic as revealed by the inspection of a very large sample (the 2,000 piece parts of Fig. 4) of the product. It will be seen that the entire characteristic lies within the specified limits, 1·137±0·001 in. Under these circumstances there will be no rejects. But suppose now that the drawing limits had been 1 137 ± 0 0005 in , i.e., that the working tolerance is "one-thou." instead of "two-thous." These conditions are shown in diagram (*b*). The

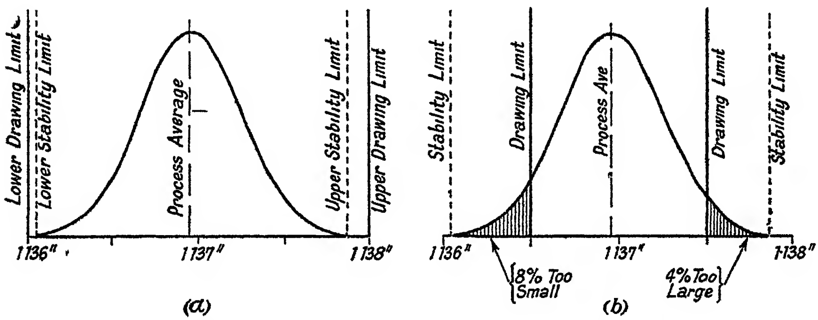


Fig. 5. EFFECT OF CHANGE IN DRAWING LIMITS ON PERCENTAGE DEFECTIVE

production characteristic remains unaltered in size and shape, but the working limits have been narrowed down. Rejects will inevitably be produced—that is only to be expected. But what percentage of the product will now be either too small or too large, or both? The answer is provided by the *areas under the production characteristic lying outside the drawing limits.*

This property of the production characteristic is unique and lies at the very heart of the quality control method. As we shall see later, it enables us to predict from a control chart the percentage of rejects to be expected in the bulk product. In the case of Fig. 5(*b*) 7·7 per cent. of the area under the production characteristic lies outside the bottom limit, and

hence, under continuing stable conditions of production, 8 per cent. of the product will be too small. At the same time, 3·7 per cent. of the area under the curve lies outside the top limit so that, if no assignable cause of variation is introduced to disturb production stability, 4 per cent. of the product will be too large.

Now let us pursue this argument to a further stage. Suppose that we are still working to the original limits of 1·137 ± 0·001 in. as shown in Fig 5(*a*), but that an assignable cause of dimensional variation has been introduced into our production process. Let us suppose, further, that this assignable cause is tool wear As we know, this particular cause of "instability" manifests itself in a dimensional drift towards, say, the upper drawing limit. Does the production characteristic give us any indication as to how soon defective piece parts will be produced and what percentage of such rejects we may expect as the result of a given amount of tool wear ? The answer is provided by Fig. 6(*a*). Here the production characteristic is turned through a right angle and the two drawing limits 1·136 in. and 1·138 in are shown as horizontal lines. Stable production conditions are shown as ending at time *O*, when the drift due to tool wear sets in. At time *A* the production characteristic begins to fall outside the top limit, and rejects start to be produced. By time *B*, when the drift due to tool wear has reached 0·0005 in. (i.e., one-quarter of the tolerance), 3·7 per cent. of the area under the production characteristic lies outside the top limit; hence the rate of defective production has reached 4 per cent.

Finally, let us consider the introduction of a different type of assignable cause of dimensional variation, say, machine wear. When a machine tool begins to show signs of wear it becomes sloppy and can no longer be used on jobs demanding high precision. In the example we have been considering, how would this effect show up as a change in the production characteristic ? What percentage of rejects would we expect to get if the precision of our auto had dropped by, say, one-half ? This time, as shown by Fig. 6(*b*), the production characteristic does not change its position but, instead, alters its shape. It spreads out and becomes flatter, showing that more and more piece parts of extreme size (high and low) are being produced than hitherto, under conditions of stable production as shown at time *O* in Fig. 6(*b*). At time *A*, the production characteristic begins to fall outside the bottom limit, whilst by the time *B* is reached it starts to fall outside the top limit as well At *C*, when the precision has fallen off by one-half, 6·5 per cent. of the area under the production characteristic lies outside the bottom limit and 4·5 per cent.

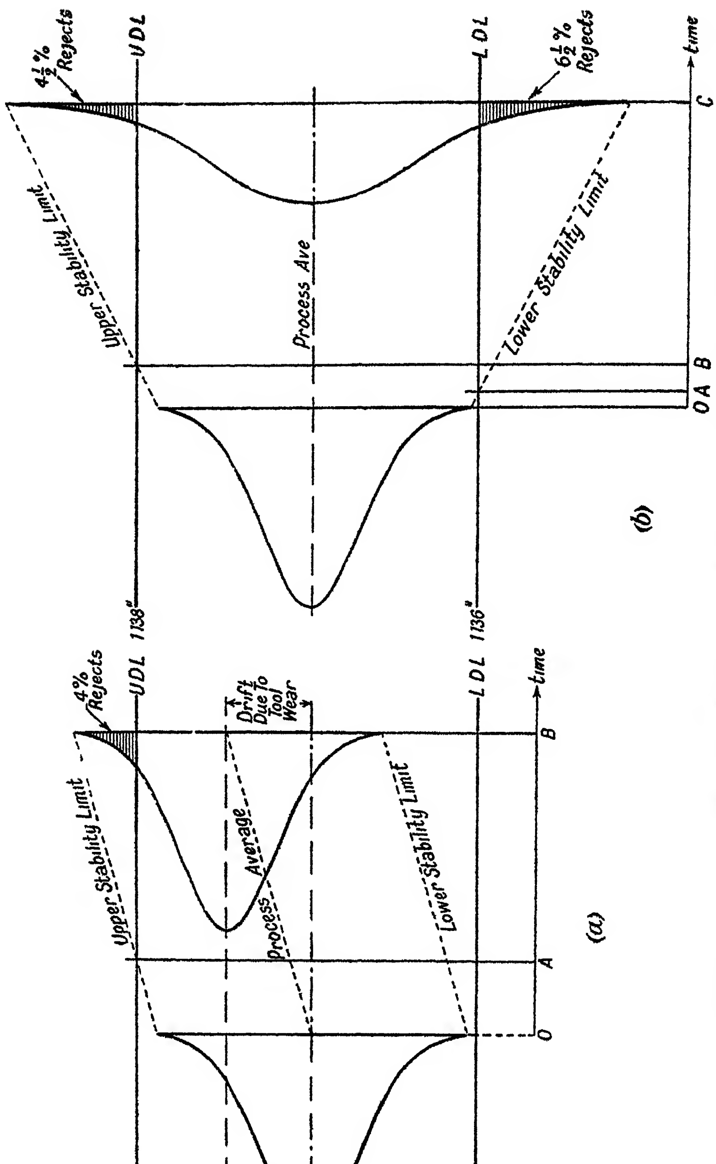


Fig. 6. Effect of Change in Production Characteristic on Percentage Defective

outside the top limit. That is to say, the drop in precision is responsible for the production of 11 per cent. rejectable piece parts.

These two examples will serve to illustrate the great importance of the production characteristic as an indicator of the expected rate of defective production. Since the main object of Quality Control is to minimise defective production, we must consider how these two basic types of variation in the production characteristic—change in position and alteration in spread—can be recognised in practice, and, furthermore, how this knowledge can be put to use in controlling the production process so as to maintain a stable characteristic. Because that, and nothing less, is the actual technique of Quality Control.

Sampling Inspection of the Production Process. We have seen that the production characteristic is an idealisation of the dimensional pattern obtained when the number of piece parts measured is very large. In other words, it is a graphic picture of the process itself when only random variation is present to cause the observed differences between one piece part and another. But this picture of dimensional variation would take too long to obtain by the straightforward method discussed in connection with Fig. 3. By the time we had got our very large number (several hundreds) of measurements the production process might have become unstable and undergone alterations of the kind illustrated by Fig. 6. What we need in order to be able to control such alterations, and so maintain a stable production characteristic, is an instantaneous picture of the production process or, rather, a continuous series of such pictures—like a cinematograph film. Such a series is to be obtained by sampling inspection.

If we go to our machine at regular intervals and each time take, instead of just one piece part, several piece parts—say, the last five produced by the machine—we obtain a succession of production characteristics in miniature as it were. Such a sample of five piece parts will exhibit a certain degree of dimensional variation, among the individuals comprising the sample, which is a miniature copy of the dimensional pattern underlying the production characteristic. At the same time there will be similar variations in dimension from one sample to the next. However, if our production process is stable, so that its characteristic remains unchanged, the variations occurring from sample to sample will be of the same order of magnitude as the variations occurring in the samples themselves. On the other hand, if the production process becomes unstable (due to the presence of assignable causes of variation),

so that its characteristic is undergoing erratic changes or systematic changes like those of Fig. 6, then the variations from sample to sample *will be greater* than the variations occurring within the samples.

The practical problem of "controlling" or stabilising a production process is one of determining the permissible limits of this variation between successive samples, in terms of the basic variation *within* the samples; and then of translating these limits to a "control chart" which will serve as a kind of cinematograph film of the production process. Before we can tackle this crucial problem, however, we need a link or connection between the dimensional variation occurring in the samples and the pattern of variation forming the stable production characteristic. This link is found to be a two-fold one and has been forged for us by the statisticians.

To appreciate the nature of this link we must go back for a moment to the bell-shaped curve expressing the so-called Normal Law of random variation underlying our stable production process. The unique feature of this curve is that it is completely defined in position, size and shape by two and only two quantities. In other words, if we are given these two quantities—known as "parameters" of the curve—and are told that they relate to a certain production characteristic, then we possess all the essential information about how the production process gives rise to a pattern of variation. From them we can predict, for example, what number or percentage of piece parts will fall inside or outside any pair of dimensional limits we may care to specify.*.

The first parameter of our production characteristic—termed the *mean* or *average* value—is a measure of the tendency for the dimensional pattern to cluster about some central value. This is clearly seen in Fig. 3, where the "centre" of the pattern is located at the dimension 1·1250 in.; or in Fig. 4, where the corresponding value is $1{\cdot}1369_4$ in. (Actually, this is the average dimension produced by the auto and, as such, is determined in the first place by the tool-setting of the machine.) From the quality control standpoint it is the most important characteristic of a production process It is denoted by the symbol "$\bar{X}$"—a capital letter x with a bar over it. If we have to talk about it at any time we call it "capital eks-bar." As we shall find out later, the use of a bar over a letter is just a simple shorthand notation for the average value of the quantity denoted

* How this can be done, and how these two fundamental quantities can be calculated from observed data, such as the 2,000 measurements of Fig. 4, need not concern us here. This is a matter of statistics rather than quality control, and has been referred to already in the footnote on p. 31.

by the letter. In dealing with quality control applications the small letter x is used to denote piece part dimension in inches, and we thus write $\bar{X} = 1{\cdot}1250$ (or $1{\cdot}1369$) for the average dimension of the production characteristic. This value is commonly known as the *process average*.

The second parameter of our bell-shaped curve—termed the *standard deviation*—is a measure of the spread of the production characteristic about the central value $\bar{X}$. Clearly two production characteristics may have the same average ; but one may be narrow and peaky, whilst the other may be broad and squat—see, for example, Fig. 6(b) or Fig. 43. Referring to the bell-shaped curve of Fig. 3, the standard deviation is actually the distance from the mean value $\bar{X}$ (middle of the curve) to the points on either side where the curvature changes from convex to concave. Its importance from the production standpoint is that it is determined by the degree of precision inherent in the production process ; the higher the precision, the smaller the standard deviation, and *vice versa*. The symbol for the standard deviation is σ, which is the Greek letter s, and is called " sigma." (There are not very many of these rather queer symbols in quality control technique and we shall soon become quite familiar with them.) *A feature of the bell-shaped production characteristic is that it falls approximately within the limits* $\bar{X} \pm 3\sigma$ (see Fig. 3). In other words, in a stable production process we never expect to find a range of dimensional variation exceeding three standard deviations on either side of the mean. These plus and minus " 3-sigma limits " thus represent the practical limits of variation encountered under conditions of stable production, and are accordingly known as the *stability limits*, or natural limits, of the production process.

These two parameters of our production characteristic, the mean or process average, $\bar{X}$, and the standard deviation, σ, determine its position and spread with regard to the drawing limits specified for the job, and hence determine the proportion of the product falling outside these limits—that is, the percentage of piece parts which will become " rejects " or " defectives." How, then, can we make use of sampling inspection results to estimate the position and spread of the production characteristic, and thus to estimate the percentage of rejectable piece parts—the so-called *percentage defective*—in the bulk product ? Bearing in mind that the several piece parts in each sample exhibit a dimensional pattern which is a miniature replica of our production characteristic, it is only natural that we should make use of two quantities of this sampling inspection pattern which correspond to $\bar{X}$ and σ for the production characteristic of the process. These two quantities are the sample *average*, denoted by $\bar{x}$

(called "eks-bar"), and the sample *range*, denoted by w The first is simply the sum of the dimensions of the several piece parts comprising the sample, divided by the number of piece parts; that is, the "common or garden" average or arithmetic mean of the sample dimensions. The second is the difference in dimension between the largest and smallest piece parts in the sample; in other words, the dimensional spread in the sample, corresponding to the spread 6σ of the production characteristic.*

These two very simple quantities—sample average $\bar{x}$ and sample range w—are linked to the parameters $\bar{X}$ and σ in the following way. Under stable production conditions, that is, if the production characteristic remains unaltered in position, size and shape, the individual values of $\bar{x}$ and w obtained by systematic sampling inspection of the production process will naturally differ slightly from sample to sample. *But their average values, taken over a large number of samples, will be sensibly constant.* This fact can be proved mathematically, and has been verified experimentally time and again The important feature of this tendency of the sample average $\bar{x}$ and sample range w towards constancy in the long run is that these two constant values are determined by the production characteristic itself. In actual fact we have —

Average value of sample averages $(\bar{\bar{x}}) = \bar{X}$ ....(1)

and

Average value of sample range $(\bar{w}) = \sigma \times$ (a numerical constant) (2)

The value of the numerical constant in expression (2) need not concern us. It depends on the size of the sample, i.e., the number of individuals in the sample, and has been worked out by the statistician in the form of a numerical table.†

The average value of the sample averages $\bar{x}$ is sometimes called the *grand average* and denoted by $\bar{\bar{x}}$ ("eks-double-bar"), but this is an unnecessary and confusing distinction as it is in practice identical with the process average $\bar{X}$. The average value of the sample ranges w is termed the *mean range* of the samples and is denoted by $\bar{w}$ ("double-you-bar"). The main point to remember is that the mean range $\bar{w}$ can be used as a substitute for the unknown standard deviation σ of the production characteristic. In other words, $\bar{w}$ is (like σ) a measure of the inherent precision of the production process. The other point to bear in mind is that the average of the sample averages $\bar{x}$—the so-called grand average of the samples— gives us the process average $\bar{X}$ directly.

* The stability limits of the production characteristic are located at $\bar{X} \pm 3\sigma$, so that the spread between them is 6σ. This spread is commonly referred to as the "natural tolerance" of the production process.

† *Cf.* Table 13 of *B.S.*600*B*—1942 (*Quality Control Charts*).

The Control Charts for Average and Range. We have already mentioned that sampling inspection of our production process will give us a "cinematograph film" of its characteristic dimensional pattern, that is, of the production characteristic. Let us assume the existence of stable production conditions in which only the random variations in piece part dimension associated with intrinsic mechanical errors are present: so that the production characteristic (*a*) maintains a fixed position with respect to the drawing limits specified, i.e., the process average $\bar{X}$ remains constant; and (*b*) keeps a fixed size and shape, i.e., its spread as measured in terms of σ remains constant. Suppose now that we go to the machine regularly, say, once an hour, and take as a sample the last five piece parts produced. At the end of a 3-days' run of six 10-hour shifts we shall have collected 60 samples, or an aggregate of 300 piece parts.

The dimensions of these 300 piece parts will form a pattern like that of Fig. 4. But what about the miniature dimensional patterns of the 60 samples taken at hourly intervals? How can we best show these so as to bring out clearly the similarity, and the difference, in pattern from sample to sample? The upper illustration in Fig. 7 provides the answer. This is the so-called dot diagram of the sampling inspection results. (Each dot represents a piece part whose dimension is given by reference to the scale at the side of the diagram.) It is a kind of "exploded view" of the production characteristic. The density of the dots is greatest in the middle region around the axis marked $\bar{X}$, corresponding to the process average or mean value of the production characteristic. The dots become thinner towards the edges of the diagram bounded by the two axes marked $(\bar{X} + 3\sigma)$ and $(\bar{X} - 3\sigma)$, corresponding to the stability limits of the production characteristic. It will be observed that no dot falls outside these stability limits. The reason is, of course, that we have assumed stable production conditions in which no piece part dimension will ever fall outside the limits defined by $\bar{X} \pm 3\,\sigma$.* The point to note about this dot diagram is the consistency of the sample pattern—the five dots representing the observed dimensions of the five piece parts in each of the 60 samples—from one sample to the next. There *are* variations, of course, from sample to sample; but these variations are of the same order of magnitude as the variations in the samples.

* Strictly speaking, this is an exaggeration. There are both theoretical and practical reasons why very occasionally, say, once in 300-400 piece parts, a dimension may very well occur somewhat outside these limits, even under ideal conditions of absolute process stability. But *as a working rule* the above statement can be accepted with confidence.

Such a dot diagram is, however, unpractical as a cinematograph film of our production process. It is too confusing. We cannot "see the wood for the trees." This is where the sample average and sample range come into their own as descriptive constants of the sample. Suppose we go back to our 60 sets of sampling inspection results, and for each one of them calculate (1) the average dimension of the five piece parts, and (2) the difference between the highest and lowest dimensions. In this way we obtain 60 values of the sample average $\bar{x}$ and 60 corresponding values of the sample range w. These are shown plotted in the middle and lower diagrams of Fig. 7. Finally, suppose we add the 60 values of $\bar{x}$ and divide the sum by 60, thus obtaining the process average $\bar{X}$; and that we add the 60 values of w and divide this total by 60 to get the mean range $\bar{w}$. These last two averages are indicated by the two horizontal axes marked $\bar{X}$ and $\bar{w}$ in the middle and lower diagrams of Fig 7.

What are the limits of fluctuation of the sample average $\bar{x}$ and range w, about their respective mean values $\bar{X}$ and $\bar{w}$, *if these fluctuations are entirely due to the random variation in piece part dimension?* In other words, what are the extreme values for $\bar{x}$ and w whose transgression will indicate to us that a significant change has taken place in our production characteristic? Or, to put the matter in a nutshell, where must one draw lines in the middle and lower diagrams of Fig. 7 which will correspond to the "stability" lines in the upper diagram? This is the crucial problem of *statistical control* (of a production process) to which we referred on p. 26, and its solution is to be found in books on mathematical statistics. However, the industrial statistician has solved the problem for us in a practical way by giving the answer in the form of very simple tables—the tables of *control limit factors* given in Appendix B. Their application will be discussed in the next chapter.

The permissible limits of variation in $\bar{x}$ and w consistent with an unchanging production characteristic, i.e., with so-called stable production conditions, are known as *control limits*. When these are included on the middle and lower diagrams of Fig. 7, such diagrams are termed *control charts*. The whole object of the quality control method is to control the production process in such a way as to maintain successive sample averages $\bar{x}$ and ranges w within their control limits. As long as we succeed in this object we know that the individual piece part dimensions *in the bulk product* will all fall within the stability limits ($\bar{X} \pm 3\,\sigma$) which form the boundaries of the production characteristic in question. In other words, *we can hope to use the results of sampling inspection to ensure that the entire output of our production process will follow a known dimensional pattern.*

The pattern *is* known because it is completely defined by $\bar{X}$ and σ, and these quantities can be obtained from the mean values of $\bar{x}$ and w given by the control charts. It is in this way that we can estimate, from the evidence provided by the control charts of a production process, the percentage of " defectives " which that process will turn out.

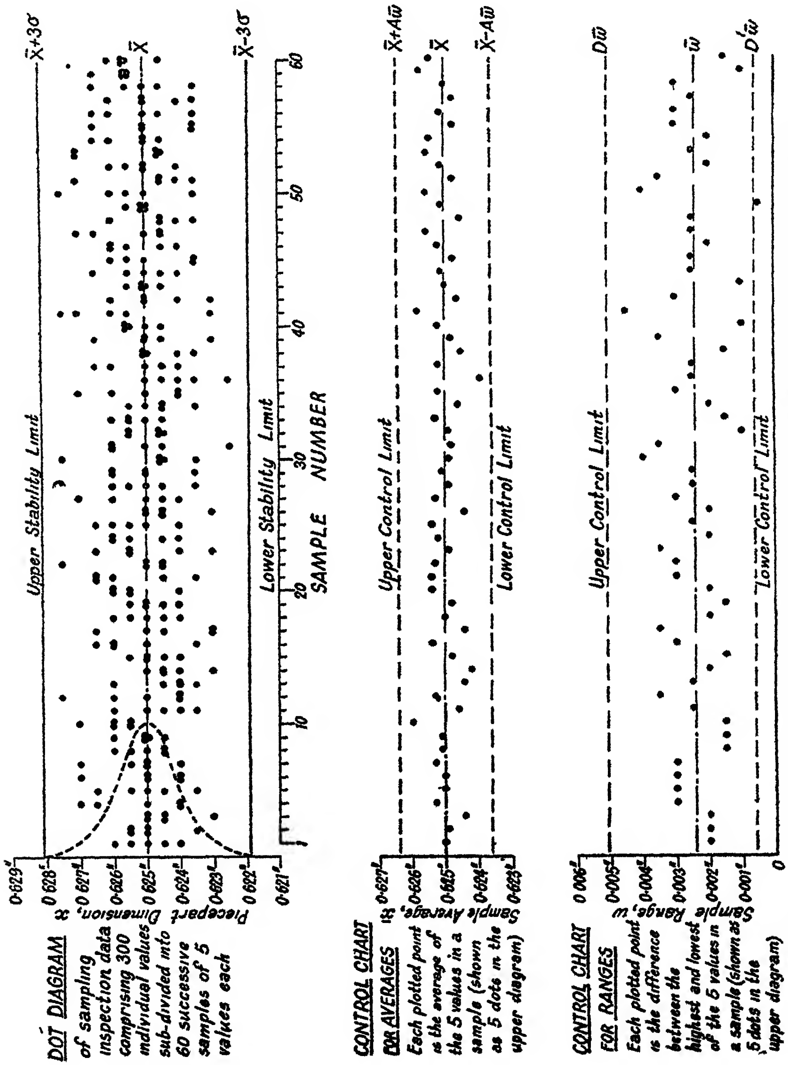


Fig. 7. THE CONTROL CHARTS DERIVED FROM SAMPLING INSPECTION DATA

We have already seen, in connection with Fig. 6, that the production characteristic can alter in two fundamental ways which are quite independent. It can change in position, that is, the process average may alter with respect to the drawing limits. And it can change in spread or, in other words, the variability inherent in the production process may alter. These two basic types of change, resulting from different kinds of spasmodic or systematic dimensional variation,* are reflected in the variations encountered from sample to sample during sampling inspection of the production process. Thus, changes in the process average $\bar{X}$ will appear as fluctuations in sample average $\bar{x}$ *which transgress the control limits on the average chart.* Similarly, changes in the precision of the process—the process variability as measured by σ, or by its equivalent $\bar{w}$ —will appear as fluctuations in sample range w *which go beyond the control limits on the range chart.* Consequently the quality control method requires two " control charts." The average chart is used to control variations in process average, e.g., due to inaccurate tool-setting or to tool wear, etc. The range chart is employed to control variations in process precision, e.g., due to inaccurate machine operation or to machine wear, etc.

The Relation Between Control Limits, Stability Limits and Drawing Limits. One of the most puzzling features of quality control technique is the fact that the control limits on the " average " chart are in practice narrower than the drawing limits specified for the production process. As we shall see in the next chapter, it is customary to show the drawing limits on the control chart for sample averages $\bar{x}$ and the corresponding drawing tolerance on the control chart for sample ranges w. As a result of this almost universal practice—and it is very sound practice—the machine-shop operatives and tool-setters not infrequently imagine that they have a legitimate grudge against those trying to introduce quality control methods. Their grievance finds common expression in such phrases as " engineering limits are reduced " by Quality Control, and hence " production is slowed down by stopping jobs that are according to drawing."

Now this grievance, as the author is only too well aware, is a very real one—the fact that it is based on a fallacy notwithstanding. To dispel it is, therefore, the most important and, perhaps, the sole " theoretical " task which the technical man concerned with quality control procedures will be called upon to perform. That, at any rate, is the author's experience after some three years' acquaintance with the quality control problems

* The so-called assignable causes of variation discussed on p. 27.

peculiar to machine-shop production. It is thus not out of place to end this somewhat theoretical chapter with a discussion of the relation between control limits, stability limits and drawing limits.

In the first place, why should the control limits on the average chart be closer to the process average $\bar{X}$ than the stability limits on the dot diagram for individuals (Fig. 7) ? The common-sense explanation is that, since an average value is (by definition) one which " averages out " the individual values from which it is derived, it does not show up the extreme values. Hence the fluctuations in the individual values will be greatly magnified as compared with the corresponding fluctuations in the average values. It is not always an easy matter to get this idea across to floor inspectors, machine operatives and tool-setters. But the following concrete example may help by way of illustration.*

READING NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
INDIVIDUAL VALUE	+10	-10	-5	+15	+5	+5	+5	0	+5	-20	+20	-10	-5	-5	+10	+5	-5	+5	-5	+10	+15	+5	+5	+5
SUCCESSIVE AVERAGES OF 2	0		+5		+5		+2 5		-7 5		+5		-5		+7 5		0		+2 5		+10		+5	
" " " " " 4	+2 5				+3 75				-1 25				+1 25				+1 25				+7 5			
" " " " " 8	+3 125								0								+4 375							

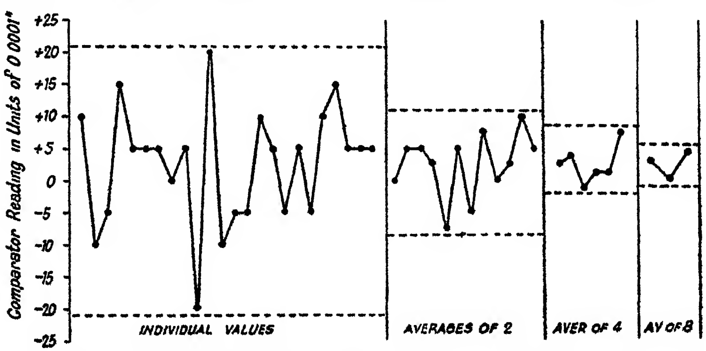


Fig. 8. How Sample Averages vary less than Individual Values

Suppose we measure 24 piece parts with a comparator whose zero is set to the nominal dimension called for on the piece part drawing, and whose readings are accurate to the nearest 0 0005 in. For convenience we shall record the plus and minus measurements in units of 0·0001 in. A typical set of results is given in the first line of the table accompanying Fig. 8. The extreme limits of variation are seen to be from -20 to $+20$, that is, a range of 0·004 in. Now let us take the averages of successive

* The author is indebted to Mr. A. W. Swan for this simple illustration.

pairs. These 12 averages are shown in the second line of the table, and it will be seen that they vary from $-7\frac{1}{2}$ to $+10$, a range of $17\frac{1}{2}$ units or just under 0·002 in. In the same way, we find the range of variation for successive averages of 4 measurements to be under 0 001 in., whilst that for averages of 8 is just under 0·0005 in. The four sets of results are shown plotted in Fig. 8.

Two important features of the law of random variation are illustrated by this rather crude example :—

(1) The variation among averages is always less than the variation among individuals.

(2) The variation among averages gets less as the number of individuals entering into the average is increased.

In terms of the control chart these two statements become :—

(1) The control limits for sample average $\bar{x}$ are always narrower than the stability limits for individual piece part dimension x.

(2) The distance between the control limits on the average chart narrows with increasing sample size.

Under conditions of stable production, when the variations in piece part dimension obey the Normal Law of Fig. 3, the above two rules follow at once from a basic theorem in mathematical statistics, which may be simply stated in the language of Quality Control .—

The spread between the control limits for sample averages is $1/\sqrt{n}$ *times the spread of the production characteristic* (i.e., between the stability limits $\bar{X}\pm3\sigma$), *where n is the sample size.*

So much for the relation between control limits and stability limits. We have already discussed the relation between stability limits and drawing limits in connection with Figs. 5 and 6. It remains to consider the basic relationship, on the one hand, between the control limits for sample average and the drawing limits; and, on the other hand, between the control limits for sample range and the drawing tolerance.

These relationships are illustrated in Fig. 9. In the majority of cases the drawing limits are specified as a nominal dimension with plus and minus limits. The distance between these limits is the drawing tolerance, and we shall henceforth denote this by $2T$.* Obviously the most economic use of this tolerance will be made if the process average $\bar{X}$ is controlled so as to fall midway between the drawing limits, as shown in Fig. 9(a). The

* As a rule drawing limits are given as D$\pm$T, where D is the nominal dimension. The special case of unequal plus and minus tolerance intervals is considered in Appendix C.

distance between the stability limits, that is, the spread of the production characteristic, is given by 6σ, so that the separation between the control limits for sample average $\bar{x}$ will be given by $6\sigma/\sqrt{n}$, where n is the sample size. The relationship between these control limits and the drawing limits $\bar{X} \pm T$ is then expressed by the *control ratio*, defined by :—

$$\text{Control Ratio} = \frac{\text{Distance between Control Limits}}{\text{Drawing Tolerance}} = \frac{3\sigma}{T\sqrt{n}} \quad \ldots\ldots \quad (3)$$

It will be seen from Fig. 9(*a*) that, provided 6σ is less than $2T$, the production characteristic will be wholly within the drawing limits, and hence the production process will not yield any defectives (i.e., piece parts whose dimensions exceed the drawing limits). The so-called critical value of this control ratio is reached when $T=3\sigma$, that is, when the stability limits coincide with the drawing limits. Under these circumstances the production process will just, and only just, meet the limits of dimensional variation specified. From equation (3) it will be seen that the critical value is defined by $1/\sqrt{n}$. Values of the control ratio for this critical condition are given in Table III for different values of sample size. For example, with samples of $n=4$ individuals, the critical value is 0·5 so that the control limits will be exactly half-way between the process average and the drawing limits.

TABLE III

Sample Size n	Critical Values	
	Control Ratio (maximum)	Relative Precision Index (minimum)
2	0·707	5·317
3	0·577	3·544
4	0·500	2·914
5	0·447	2·580
6	0·408	2·368
7	0·378	2·219
8	0·356	2·108
9	0 333	2·020
10	0·316	1·950

$$\text{Control Ratio} = \frac{\text{Distance between Control Limits}}{\text{Drawing Tolerance}}$$

$$\text{Relative Precision Index} = \frac{\text{Drawing Tolerance}}{\text{Mean Sample Range}}$$

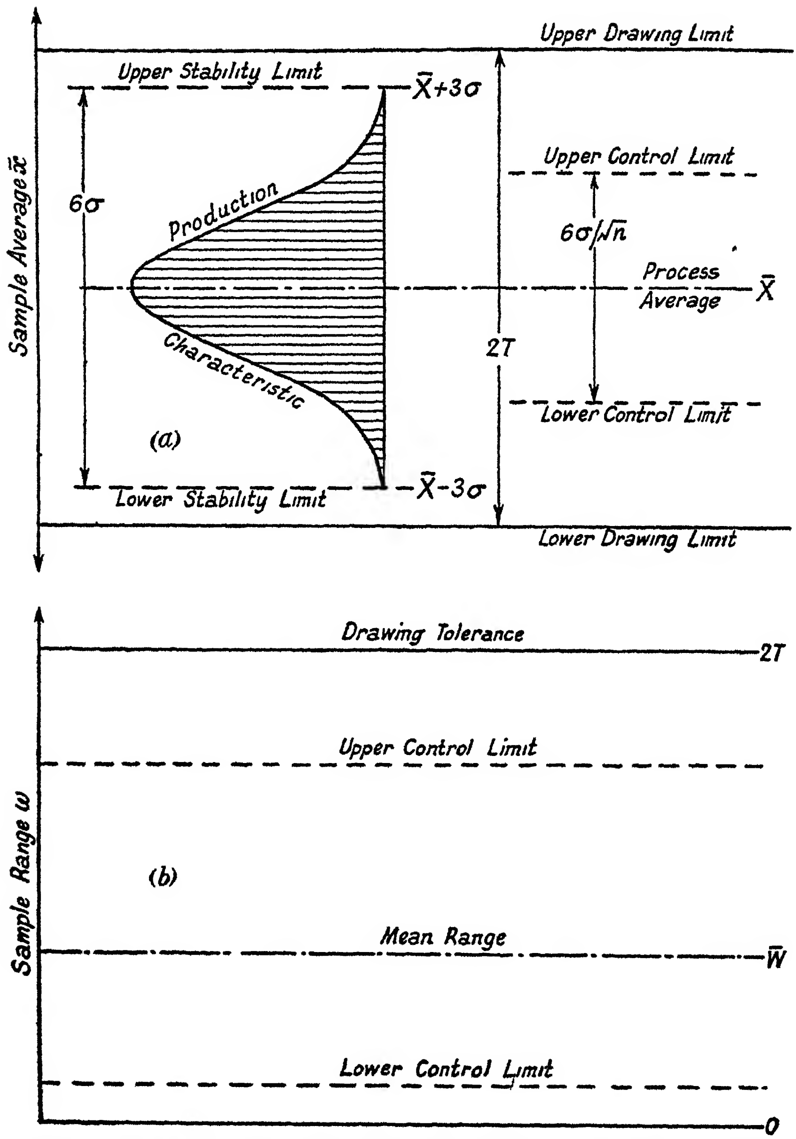


Fig. 9. RELATION BETWEEN CONTROL LIMITS AND DRAWING LIMITS

Fig 9(b) shows the corresponding relationship between the control limits for sample range w and the drawing tolerance $2T$. This relationship is expressed by the *relative precision index*,* defined by

$$\text{Relative Precision Index} = \frac{\text{Drawing Tolerance}}{\text{Mean Sample Range}} = \frac{2T}{\bar{w}} \quad \ldots\ldots\ldots (4)$$

It will be remembered that $\bar{w}$, being equivalent to σ in accordance with equation (2), is thus a measure of the inherent precision of the production process. The poorer the precision, the greater will be $\bar{w}$ (and σ) and, in consequence, the nearer will the stability limits approach the drawing limits. As in the case of the control ratio, there is a certain value of the relative precision index for which the stability limits and the drawing limits coincide. At this critical value the production process will just, and only just, begin to yield defectives. Values of the relative precision index—commonly denoted by R.P.I.—for this critical condition are also given in Table III for different values of sample size. For example, with a sampling inspection routine in which the patrol inspector takes the last five piece parts produced during the inspection interval ($n=5$), the critical value of the R P.I. is 2·6. Hence, provided the mean sample range does not exceed a value equal to the drawing tolerance divided by 2·6, and provided the process average is controlled at a value midway between the drawing limits, the production process will meet the specified tolerance.

The practical importance of the R.P.I. as a measure of the capacity of a production process (including machine, tool-setter, operator, and raw material) to meet specific limits of dimensional variation will be considered in detail in the next chapter. It is a much more useful measure than the control ratio, in spite of the fact that the latter has the merit of being readily visualised as a spatial relationship in the control chart for sample averages. The main objection to the use of the control ratio is that its value depends on the sample size as well as upon the characteristic of the production process, and hence its evaluation from the sampling inspection data underlying the control chart requires rather more arithmetic than is practically convenient. This is at once seen by comparing equation (3) with equation (4).

* This term was first used by Dudding and Jennett, in their work on Quality Control during the later war years See Reference 1.2 in Appendix A.

CHAPTER IV

CONTROL CHARTS BASED ON DIMENSIONAL MEASUREMENT

THE scientific approach to the problem of controlling product quality during manufacture, in order to minimise the production of defective components, which has been made in the last chapter is perhaps not the most straightforward nor the easiest to follow in practice. But this dimensional method of Quality Control is by far the most powerful and thus the most important, and in the author's experience its study and application produces, moreover, a better and more permanent understanding of the root problem of product quality than is to be obtained through using the simpler alternative, the so-called method of defectives.

That method of Quality Control, based on the counting of defectives, and thus ideally suited to visual inspection and to the checking of dimensions by limit gauges, has the undoubted merit of operational simplicity, which in many cases more than outweighs its lack of sensitivity as compared with the method based on dimensional measurement. Moreover, some very recent theoretical development in the method of defectives has placed it on a better competitive footing and, as a result, the present emphasis on quality control systems involving direct or comparative measurement of piece part dimensions may well make way for a vogue of quality control procedure having the manual, mechanical or even electrical gauging of piece parts as its functional basis.

It is perhaps fitting that this latest development in quality control technique should have been made by that same English statistician, L. H. C. Tippett, whose earlier work on the properties of the sample range made possible the practical application of dimensional control charts to everyday machine-shop practice. But for his mathematical researches the exceedingly powerful method of Quality Control based on dimensional measurement would have remained perforce a specialists' instrument, rather than a workaday tool that can safely be placed in the hands of ordinary production and inspection personnel.* The purpose of

* When the author first started to apply quality control methods to machine-shop production in 1940 he was unaware of Tippett's development of the range as an alternative to the standard deviation in the case of small samples. The difficulty of trying to introduce a quality control routine involving the calculation of a root-mean-square deviation *for every sample* can be imagined! This difficulty presented such an insuperable obstacle to any practical scheme of quality control that the author's attempts at devising one had to be abandoned in spite of the obvious benefits that were being gained from a few experimental control charts. It was more or less by chance that some months later he came across Tippett's original paper in *Biometrika* and was thus able to make headway, using the by now universal method of calculating control limits from the mean sample range.

the present chapter is to describe the use of that tool as a machine-shop aid and to outline the operational procedures appropriate to the application of Quality Control by dimensional measurement under a variety of conditions to be encountered in practice. Consideration of quality control technique based on the method of defectives, involving as it does a quite different approach to the quality problem, is deferred to the next chapter.

How to Start a Control Chart. When selecting a production process for an initial experiment in applying quality control technique, it is as well not to be too ambitious. Choose for preference a job answering to the following requirements :—

(*a*) The process operation should be a familiar one, whose general behaviour is well known by production and inspection personnel alike.

(*b*) The machine employed for the job should be one that can be relied upon to give a good run without attention other than for purposes of ordinary re-setting.

(*c*) The dimension chosen for control should be one that can be readily measured by the usual shop micrometer or dial gauge.

(*d*) The tolerance on this dimension should be big enough to ensure that the machine chosen is fully capable of maintaining the dimension within the drawing limits. (In other words, choose a job where the percentage of product rejected is negligible under normal conditions.)

A good example of a job eminently suited to a first try-out of Quality Control would be a capstan turning operation on a shouldered bush, to give *inter alia* a shoulder diameter of $0{\cdot}625 \pm 0{\cdot}003$ in. (See Fig. 32.) By way of contrast the type of job *not* to choose would be the production of an internal bore on a multi-spindle auto.

When a convenient production process has been selected, the next point to be decided is the sampling inspection procedure. Here the following rules should be observed :—

(*e*) Visit the machine at regular intervals and at each visit *take the last few components produced.** The measured values of piece part dimension obtained from these components constitute the sample of product whose dimensional pattern is a miniature copy of the production characteristic.

* Under certain circumstances it may be desirable instead to take the components at random from among the total produced during the preceding interval The respective merits of "instantaneous" and "random" sampling inspection will be discussed at the end of the present chapter.

(*f*) The number of individuals in the sample—termed the *sample size* and denoted by n—should not be more than ten, and preferably not less than four. From the standpoint of practical convenience $n=5$ has proved to be the most acceptable sample size.

(*g*) The sample size having been decided, the time elapsing between successive visits to the machine—termed the *inspection interval*—should be so chosen that the sample represents between 5 and 10 per cent. of the output from the machine during each interval.

The appropriate inspection interval is readily calculated from the formula :—

$$\text{Inspection interval} = (\text{sample size}) \times (\text{production-cycle time}) \times (10 \text{ to } 20) \quad . \quad . \quad . \quad (5)$$

It should be noted that the lowest value given by this formula corresponds to 10 per cent. sampling inspection, whilst the highest value corresponds to a sampling inspection figure of 5 per cent. In using the formula it is good practice to choose a convenient inspection interval, such as 15 minutes, half an hour, or one hour, rather than values like 25 minutes or an hour and a quarter, such as might correspond to some preconceived figure of percentage inspection.

The sampling procedure having been decided upon, it remains to settle the question of recording the inspection data in a form convenient for the plotting of control charts. Here it is necessary to emphasise the importance of recording and tabulating such data in a systematic manner which will reduce to an absolute minimum the arithmetical work of calculating the sample average $\bar{x}$ and range w. It goes without saying that the best method to adopt is to lay out a data sheet on which can be entered not only the sampling inspection results but also any additional information relevant to the job, such as drawing, machine and dimension references ; production-cycle time, inspection interval and sample size ; date, shift and time of inspection , check numbers for operator, machine tool-setter, and patrol inspector (if the actual work of inspection is left to the latter, rather than to a more responsible person in charge of the quality control experiment). An example of a suitable data sheet is given in Table IV.

TABLE IV—Typical Data Sheet for Recording of Sampling Inspection Results

* Part No.	Section	M/C No.	Process Operation	Dimension	Tolerance	Production Cycle Time	Sample Size	Inspection Interval
PB.4197	CAPSTANS	47	Turn O.D. of Shoulder	0·625″	±0·003″	1·24 mins.	5	1 hr.

Date and Shift	16/8/40—DAY										16/8/40—NIGHT									
Time of Inspection	9 00	10.00	10.50	12.05	1.00	2.10	3.05	4.15	5.15	6 20	8.30	9.40	10.45	11.40	12.45	1.50	3.00	3 55	5.10	6.15
Piecepart Dimension, x — Individual Measurements constituting the Sample — 1st	6250	·6260	·6235	50	65	55	40	45	55	50	75	55	50	50	65	55	60	65	50	80
2nd	·6245	6250	*50	60	65	70	60	50	40	50	55	45	60	75	60	80	60	50	55	55
3rd	·6250	6265	*55	60	45	40	60	30	40	35	60	60	55	65	60	55	70	70	75	60
4th	·6250	·6240	*40	40	60	35	45	55	45	50	50	70	60	55	50	55	50	40	60	50
5th	·6235	6265	*50	55	65	65	55	45	35	45	65	55	65	65	55	70	60	55	70	65
Total	3·1230	3·1280	*230	265	300	265	260	225	215	230	305	285	290	310	290	315	300	280	310	310
Average, $\bar{x}$	6246	6256	*46	53	60	53	52	45	43	46	61	57	58	62	58	63	60	56	62	62
Range, w	·0015	·0025	*20	20	20	35	20	25	20	15	25	25	15	25	15	25	20	30	25	30
Operator	1126		.	..	..	.	.			1126	1237	.	.	.	.	.				1237
Setter	348	..	..	..	..	.	..	..	.	348	219	..	..	..	..	..	..	..	..	219
Inspector	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

* Hereafter the first two figures are no longer recorded.

The five individual piece part dimensions constituting each sample are entered in successive columns At the foot of each column are recorded the total of the five dimensional values; the sample average $\bar{x}$, viz., this total divided by the sample size $n=5$; and the sample range w, viz., the difference between the highest and lowest values observed in the sample. Considerable time and labour are to be saved by dropping the first two figures after the decimal place, as these occur in every dimension. In this particular example the measurements were made on a shop micrometer read to the nearest 0 0005 in. An alternative method, leading to a similar reduction in the amount of arithmetical working, is available if the measurements are made with a comparator or dial gauge whose zero is pre-set to coincide with the nominal dimension called for on the drawing—in this case 0·625 in. The five measurements constituting the seventh sample (recorded at 3.05 p.m. in Table IV) would then read as follows :—

$$-10, \ +10, \ +10, \ -5, \ +5$$

each unit being 0·0001 in. The sum of these five deviations from zero (i.e., from the nominal dimension) is $+10$ which, divided by 5, gives an average value of $+2$. Hence the required value of $\bar{x}$ is $0{\cdot}6250+0{\cdot}0002=0{\cdot}6252$ in. Similarly, the difference between the highest and lowest deviations from zero is $+10-(-10)=20$, giving $w=0{\cdot}0020$ in.

The twenty values of $\bar{x}$ and w are shown plotted in Fig. 10 against the successive times of inspection. These two graphs are the *control charts* for the dimension in question. For plotting such charts any cheap form of squared paper can be used. There is no point in using expensive paper in which the square ruling is dimensionally accurate—so-called "machine divided" graph paper. The most convenient type of graph paper is perhaps that ruled in inch squares, sub-divided into $\frac{1}{10}$-inch squares. In plotting control charts choose a scale which is easily read. Experience has shown the following scales to be those generally most suitable .—

Drawing Tolerance	$\pm$ Limits	Scale
0·002″ and under	±0 001″ and under	1 inch = 0·001″
0·002″ to 0·005″	±0 001″ to ±0·0025″	1 inch = 0·002″
0·005″ to 0·010″	±0 0025″ to ±0·005″	1 inch = 0·005″
0·010″ and over	±0·005″ and over	1 inch = 0·010″

On the " average " chart the drawing limits should be shown as solid lines extending right across the chart. Similarly, on the " range " chart the drawing tolerance should also be shown as a solid line. For it represents the limiting value of sample range beyond which " defectives "

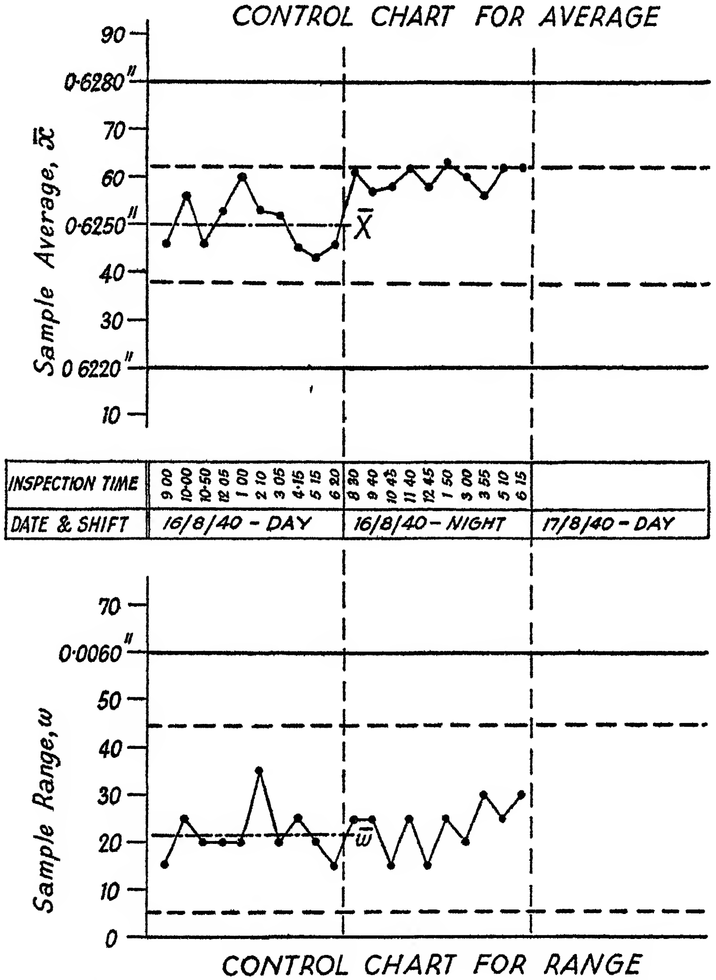


Fig. 10. CONTROL CHARTS FOR DATA OF TABLE IV

are bound to occur. In other words, for a sample in which the value of w exceeds the drawing tolerance, *one or more individuals in the sample must be outside the drawing limits.*

Finally, the control charts for average and range must be completed by insertion of their respective *control limits*. These, it will be recalled, define the maximum fluctuation in $\bar{x}$ and w which will occur in practice if the production characteristic is stable, that is, remains unaltered in position and shape. They are readily calculated from the initial sampling inspection results, covering preferably not less than 50 individual measurements. Thus, with a sample size $n=5$, the first ten samples will give enough information to enable a reliable estimate of the production characteristic to be made, from which the control limits can be calculated. A convenient data sheet for this purpose is shown in Table V.

TABLE V

TYPICAL DATA SHEET FOR CALCULATING CONTROL LIMITS

Sample Number	Average $\bar{x}$	Range w
1	0 6246	0·0015
2	56	25
3	46	20
4	53	20
5	60	20
6	53	35
7	52	20
8	45	25
9	43	20
10	46	15
Total :	6 2500	0 0215

PROCESS AVERAGE : $\bar{X} = \frac{1}{10}(6{\cdot}2500) = 0\ 6250''$
MEAN SAMPLE RANGE : $\bar{w} = \frac{1}{10}(0{\cdot}0215) = 0\ 0022''$

Control limits for $\bar{x}$: $\bar{X} \pm A\bar{w} = 0\ 6250 \pm (0\ 59 \times 0\ 0022) = 0{\cdot}6263''$ and $0{\cdot}6237''$

Control limits for w : $\begin{cases} D\bar{w} = 2\ 09 \times 0{\cdot}0022 = 0{\cdot}0046'' \\ D'\bar{w} = 0\ 25 \times 0{\cdot}0022 = 0\ 0006'' \end{cases}$

DRAWING LIMITS $= 0{\cdot}625'' \pm 0{\cdot}003''$

RELATIVE PRECISION INDEX $= \frac{2T}{\bar{w}} = \frac{0\ 006}{0{\cdot}0022} = 2{\cdot}7$

CONTROL RATIO $= \frac{A\bar{w}}{T} = \frac{0{\cdot}0013}{0{\cdot}003} = 0{\cdot}43$

The procedure is as follows :—

(1) Add the 10 values of $\bar{x}$ and divide the resulting sum by 10. This gives the *process average*, $\bar{X}$.

(2) Add the 10 values of w and divide the resulting sum by 10. This gives the *mean sample range*, $\bar{w}$.

(3) Look up Table VII in Appendix B and find the value of the factor A corresponding to the sample size $n=5$.

(4) Multiply the mean sample range by this factor to obtain the dimensional quantity $A\bar{w}$.

(5) First add, and then subtract, this quantity from the process average. This gives the *control limits for sample average*, $\bar{X}\pm A\bar{w}$. These should be shown on the average chart (Fig. 10) as dotted lines.

(6) Look up Table VII in Appendix B and find the values of the factors D and D' corresponding to the sample size $n=5$.

(7) Multiply the mean sample range by these factors to obtain the *control limits for sample range*, $D\bar{w}$ and $D'\bar{w}$. These should likewise be shown as dotted lines on the range chart (Fig. 10).

In the present example of a simple capstan turning operation the first ten plotted points were charted on the day shift, and the second ten points during the following night shift. The control limits of Fig. 10 thus correspond to the day-shift production. It will be observed that the tool-setting was accurate in that the process average coincides with the "engineering mean," i.e., the nominal dimension midway between the drawing limits. At the same time all the first 10 values of $\bar{x}$ fell within the control limits, as did the corresponding values of w. The production process was therefore stable as regards both dimensional level and variability. In other words, during the day shift in question the production characteristic maintained unaltered its position and its spread with respect to the drawing limits.

How are we to interpret, in turn, the results for the following night shift? Here the range chart is still "in control"—no points outside the control limits—but the average chart shows a certain "lack of control," for several points are almost on the upper control limit, whilst one has fallen just outside it. This is to be interpreted as a significant upward shift in the dimensional level of the production process. As a matter of fact, the process average for the second 10 points is found* to be $\bar{X}=0{\cdot}6260$ in. Thus the production characteristic has been moved bodily upwards through 0 001 in. Investigation showed that this was accounted for by the machine having been re-set by the tool-setter on the night shift, before production was resumed.

Before going on to consider what further information such control charts provide, it will be as well, perhaps, to clear up a small point which

*Following the method of calculation set out in Table V.

is often puzzling to those making their first start with Quality Control, The question is often asked. What is the object of the lower control limit $D'\bar{w}$ in the range chart ? In so far as control limits are pointers to the necessity for some action being taken with regard to the production process, it is clear that a point on either chart falling outside either control limit is an indication of " lack of control "—of the need for taking corrective action For instance, a point on the average chart above the upper control limit $\bar{X}+A\bar{w}$ means that the process has changed in the direction of producing too many piece parts of larger shoulder diameter than 0·625 in Similarly, a point falling outside the lower limit $\bar{X}-A\bar{w}$ indicates a corresponding change towards the production of too many piece parts having shoulder diameters smaller than that aimed at. Again, a point on the range chart outside the upper control limit $D\bar{w}$ shows that the precision—the closeness with which the same dimension can be repeated—has deteriorated from the standard set by the initial results, from which all the control limits were calculated. Hence a point falling *below* the lower limit $D'\bar{w}$ simply means that the precision of the production process *has improved.* The occurrence of such a point (e.g , that for the 49th sample in Fig. 7) does *not* call for corrective action because it indicates a significant change for the better. In fact, if several points fall near or below the lower control limit in the range chart it may be worth while conducting an investigation to ascertain the cause of the improvement in precision, with a view to maintaining the improvement as a permanent feature of the production process.

The R.P.I. as a Guide to the Setting of Control Limits. Apart from indicating whether or not the production process is stable, as regards dimensional level or variability, or both, do the control charts of Fig. 10 reveal any other useful information ? For example, what evidence do they provide that the specified tolerance of $\pm 0{\cdot}003$ in. can be met with the machine, production set-up, and operators doing this particular job ? In other words, can we tell from the control charts that the production of scrap is either inevitable, avoidable with care and attention, or unlikely under normal circumstances ?

Broadly speaking, the answer to this question is " Yes." But an unqualified affirmation can only be given *if the range chart is in control.* This proviso is important and yet is frequently overlooked in practice. It so happens that, in our example of Fig. 10, all the points in the range chart fall inside their control limits. We conclude, therefore, that the precision of the process is constant—that its dimensional variability is basically random. And, on the basis of this conclusion, we are justified

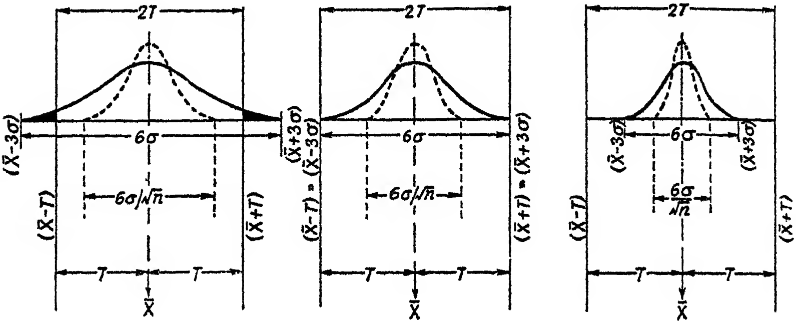
in calculating the mean sample range $\bar{w}$ as a measure of the random variability,* and in using $\bar{w}$ to set limits on the variation (due to chance causes alone) of both sample average $\bar{x}$ and sample range w.

In practice, however, we are commonly confronted with a production process whose precision changes erratically or even systematically. In capstan work, for instance, the precision varies from instant to instant with the vagaries of the operator. In the case of autos, to cite another example, the precision will often fluctuate with the temperature of the coolant When plotting control charts in such cases, therefore, it is quite likely that the range chart will show lack of control. The very first step in the application of quality control technique to a production process of this kind consists in searching for, finding and, if possible, eliminating the assignable causes of non-random variation that are reflected in "outsiders"—points outside control limits—on the range chart. *This is not a statistical problem.* It is a straightforward engineering problem, calling for a *practical* knowledge of machines and production processes together with some experience in diagnosing their peculiar ailments. As a matter of fact, this is not as difficult as it sounds. Take, for instance, a typical capstan control chart like Fig. 12. Here the dimensional variation is largely under the operator's control. It would not be impossible to eliminate the few outsiders in the range chart, and, incidentally, to reduce the process variability (measured by $\bar{w}$), by fitting a dial gauge to the capstan stop and making the operator work to the same "pressure" indication all the time. In fact, the author has come across instances where this has actually been done. As an alternative form of instability shown by the range chart there is the gradual upward drift in the pattern of range points associated with machine wear (e g , bearing trouble). Here the occurrence of outsiders in the range chart is not so much an erratic phenomenon as a gradual but persistent transgression of the upper control limit $D\bar{w}$. The remedy for such a relatively steady deterioration in process accuracy is clearly a general overhaul of the machine.

Thus the bringing of a range chart into control will not rarely be an impossible task. *Once such a chart does show evidence of control,* the question as to whether or not the production process is inherently capable of meeting its specific tolerance can be decided fairly readily and quite satisfactorily. The decision is most conveniently made with reference to the relative precision index (R.P.I.) discussed at the end of Chapter

* I.e., of the unchanging "standard deviation" σ of the production characteristic.

III. It will be recalled that at a certain critical value of this index, as determined from an actual range chart, the stability limits $\bar{\bar{X}} \pm 3\sigma$ and the drawing limits $\bar{X} \pm T$ coincide, so that the production process will just meet its specified tolerance. If the observed R.P.I. is *less* than this critical value, the stability limits fall outside the drawing limits and *the*



Low R.P.I. (a) — Medium R.P.I. (b) — High R.P.I. (c)

Fig. 11. RELATION BETWEEN STABILITY LIMITS AND DRAWING LIMITS FOR DIFFERENT R.P.I. VALUES

production of scrap is inevitable. On the other hand, if the observed R.P.I. is *greater* than the critical value, the stability limits fall inside the drawing limits and *the production process is too accurate for its specified job.*

These alternatives lead to important differences in the method of setting control limits on the average chart. In practice we have to consider three cases as follow :—

(1) *Low Relative Precision*: R.P.I. less than the critical value.

(2) *Medium Relative Precision* R.P.I. between the critical value and approximately $1\frac{1}{3}$ times that value.

(3) *High Relative Precision*. R.P.I. greater than about $1\frac{1}{3}$ times the critical value.

The numerical values of the R.P.I. corresponding to these three cases are given in Table VIII of Appendix B.

Case (1) is illustrated in Fig. 11 (*a*). The critical condition of Case (2) is shown in Fig. 11 (*b*). Case (3) is depicted in Fig. 11 (*c*). In all three diagrams the control limits for sample average are indicated by the dotted lines inside the drawing limits.

Case (1). *Low Relative Precision.* A good practical illustration of this condition is given by the control charts of Fig. 12 relating to a capstan turning operation of a somewhat exacting nature, calling for a tolerance of $\pm 0{\cdot}0005$ in. on a nominal dimension of 0·1578 in The sampling inspection results for the initial period (June 3rd—6th) were used to calculate a provisional mean range $\bar{w}_0$ on which the control limits for $\bar{x}$ and w for the remainder of the run were based. Here $\bar{w}_0 = 0{\cdot}0006$ and the sample size was $n=4$, so that $D\bar{w}_0 = 2{\cdot}26 \times 0{\cdot}0006 = 0{\cdot}00135$, whilst $\bar{X} \pm A\bar{w}_0 = 0{\cdot}1578 \pm (0{\cdot}75 \times 0{\cdot}0006) = 0{\cdot}1582$ and 0·1574.* It will be seen that the attempt to achieve control of the sample average (i.e., the dimensional level of the process) was reasonably successful towards the end of the run. The important point to note, however, is that the control limits are too close to the drawing limits. In fact, the control ratio (*cf.* Table III) is well above the critical value of 50 per cent for $n=4$. Hence the production of scrap is inevitable *whether the average chart is brought into control or not.*

Now this particular job had in the past always given trouble in that no matter how much attention was paid by the tool-setter, or how much care was exercised by the operator, anything up to 15 per cent. defectives were found in batch after batch. The reason for this at once becomes clear from a consideration of the R.P.I. of the production process. Analysis of the sampling inspection results for this particular batch yielded a process average of $\bar{X}_1 = 0{\cdot}1578$, coinciding with the nominal dimension—so that the tool-setting was accurate enough The mean sample range was found to be $\bar{w}_1 = 0{\cdot}0005$, slightly less than the initial value used in setting the control limits. Hence in this case we get for the R.P.I.

$$\frac{2T}{\bar{w}_1} = \frac{0{\cdot}001}{0{\cdot}0005} = 2{\cdot}0$$

which is considerably less than the critical value 2·9 for samples of four.

In such cases the minimum percentage of work produced outside the drawing limits can be found from Fig. 13. This minimum value is to be expected, of course, only if the average chart remains in control—which is not the case in Fig. 12. Referring to Fig. 13, however, it will be seen that an R.P.I. of 2·0 with $n=4$ corresponds to an expected minimum of some 4 per cent. defectives in the product turned out from this particular process. A detailed inspection of the completed batch actually yielded $5\frac{1}{2}$ per cent. defectives. Both charts in Fig. 12 for this first batch clearly

*Strictly speaking, the range chart during this period was not in control, so that these limits could only be regarded as tentative.

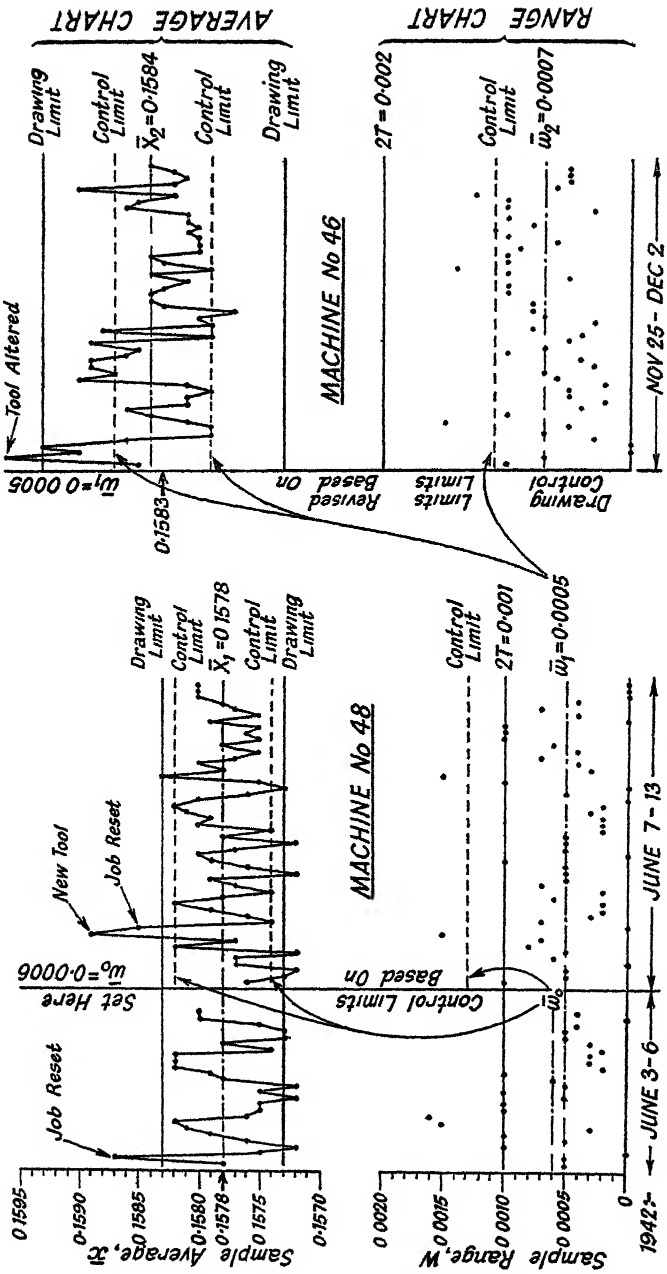


Fig. 12. Quality Control of Two Successive Batches (Capstan Operation)

indicate the occurrence of defectives, quite apart from a consideration of the R.P.I. for the process. On the one hand several sample averages fell either on or outside the drawing limits, so that the individuals in these samples must have been well outside. On the other hand, a number of sample ranges exceeded the drawing tolerance, so that at least one individual in each of these samples must have been outside one of the drawing limits.

The control charts thus provide pretty conclusive evidence that the specified drawing limits are too tight for the job as planned for this particular capstan. What action, then, should be taken under such

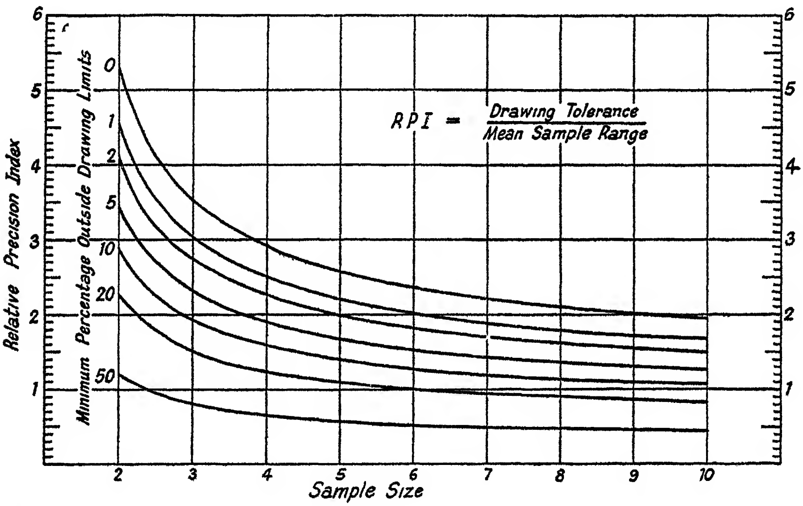


Fig. 13. Relation between R.P.I. and Rate of Defective production

circumstances? *Clearly, the action demanded is anything which will increase the relative precision of the production process.* Since the R.P.I. is the ratio of the drawing tolerance to the mean sample range, there are two alternative courses of action. Either the drawing tolerance must be increased or the process variability—as measured by the mean sample range—must be reduced. Failing either of these two measures, the production of defectives cannot be prevented but can only be minimised.

The first step, then, where the R.P.I. is found to lie below the critical value, is to seek an increase in the drawing tolerance. In the particular case illustrated in Fig. 12 the design department agreed to a raising of the upper drawing limit by 0·001 in., thereby doubling the tolerance.

(No individual piece part dimension below the existing limit of 0·1573 in., however, could be tolerated, as such low dimensions would prevent the proper functioning of the piece part on assembly.*) The control charts for the next batch of components, produced under the new limitations, are shown on the right of the illustration. The control limits were calculated from the mean sample range of the preceding batch, $\bar{w}_1=0{\cdot}0005$ in. The aimed-at process average $\bar{X}$ became 0 1583 in. instead of the previous 0·1578 in , so that the control limits on the average chart were placed at $\bar{X}\pm A\bar{w}_1=0\ 1583\pm(0{\cdot}75\times0\ 0005)=0{\cdot}1587$ and 0·1579. Similarly, the control limit on the range chart was located at $D\bar{w}_1=2{\cdot}26\times 0{\cdot}0005=0{\cdot}0011$. It will be seen that, although stability of production was by no means fully achieved, the increase in relative precision led to a more satisfactory position as regards rejects. The achieved process average was $\bar{X}_2=0{\cdot}1584$ in., sufficiently close to the aimed-at value, whilst the mean sample range this time worked out at $\bar{w}_2=0{\cdot}0007$ in. Hence the R.P.I. was in this latter case 0 002/0·0007=2·9, which is just on the critical value. As a matter of interest, subsequent runs of this same operation showed that a mean sample range of $\bar{w}=0\ 0005$ could be maintained with a reasonable degree of control, and in fact no defectives are now produced unless the average chart exhibits a lack of control (of dimensional level or process average $\bar{X}$)

Of course it may not always be possible, as in this example, to obtain an increase in the drawing tolerance. Under these circumstances one must adopt the alternative course of attempting to reduce the mean sample range $\bar{w}$. As a practical problem this means that efforts must be made to reduce the process variability, that is, to increase the precision of the production process. An obvious way of doing so is to plan the job on a better class of machine (if one is available), otherwise the tooling must be replanned to achieve the desired result. If neither alternative is a practical possibility, then the existing machine must be examined with a view to reducing its variability. The procedure to adopt will then be similar to that described in the preceding section, in connection with the bringing of a range chart "into control."

Finally, if no means can be found to increase the R P.I. of the production process, one must face the fact that rejects will inevitably be produced. The problem then becomes one of *minimising the percentage of defectives*. A little consideration will show that this problem will present itself in two forms. In the first place, if it is immaterial whether defective

* I.e., the drawing limits were originally $0{\cdot}1573\begin{cases}+0{\cdot}001\\-0\end{cases}$

production is due to transgression of the upper or the lower drawing limit, the most economic course to follow is to aim at a process average half-way between these limits, and in this manner to equalise the percentages of "high" and "low" defective piece parts. In the second place, if *one* of the two limits may on no account be exceeded, then the process average to aim at will be one which will cause all the rejects to be produced by the inevitable transgression of the *other* limit.* An example of the first case might be a simple length or depth. Examples of the second case are critical internal and external diameters.

To facilitate the estimation of the minimum percentage of defectives to be expected in these two cases the charts in Appendix C have been prepared. These enable values of percentage defective to be found in terms of the R.P.I., and the amount by which the process average $\bar{X}$ must be "off-set" from the nominal drawing dimension in the second case. It must be remembered, however, that these percentages are *minimum* values, corresponding to a close control of the process average through the medium of the control chart for sample averages $\bar{x}$.

Case (2): *Medium Relative Precision.* As an example of this condition of applying quality control technique to a production process we shall take a pressing operation involving the simultaneous control of two dimensions. The piece part in question is the brass capsule case forming part of the microphone of a telephone transmitter and shown diagrammatically in Fig. 14.† The form illustrated is produced on a 150-ton press after three previous draws from a brass slug about 0·050 in. thick. These capsule cases are produced in very large quantities and this particular pressing operation takes place at a rate of some 500 per hour.

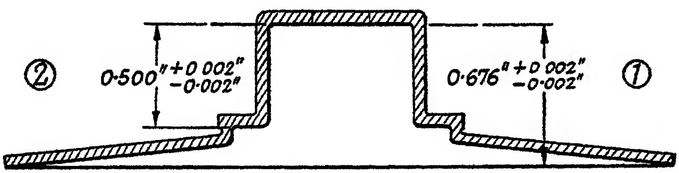


Fig. 14. Section of the Microphone Capsule Case showing the Two Dimensions produced by a Pressing Operation

* The point here is that transgression of the one limit means the production of *scrap*; whilst transgression of the other limit means the production of *rejects*—defective piece parts which can be corrected by a further operation.

† This particular job is briefly described, and illustrated by several photographs, in the first article of a series entitled "Quality Control in Operation" published in the *Production and Engineering Bulletin* for December, 1943. (This Bulletin was issued jointly by the Ministry of Production and the Ministry of Labour and National Service.)

Trouble was being experienced in adjusting the punch and die, and the weight of the press, to produce a satisfactory dimensional level. In spite of repeated adjustments too many defectives were occurring, either on dimension No. 1 or dimension No. 2. It was, therefore, felt that control charts should be maintained in the hope that the cause of the trouble would be revealed, for a tolerance of 0 004 in. ought to be ample in a case such as this. A sample of 5 was taken every hour and the two dimensions indicated in Fig. 14 were measured to the nearest 0·0005 in on comparator type gauges fitted with special adaptors. Fig. 15 shows the plot of $\bar{x}$

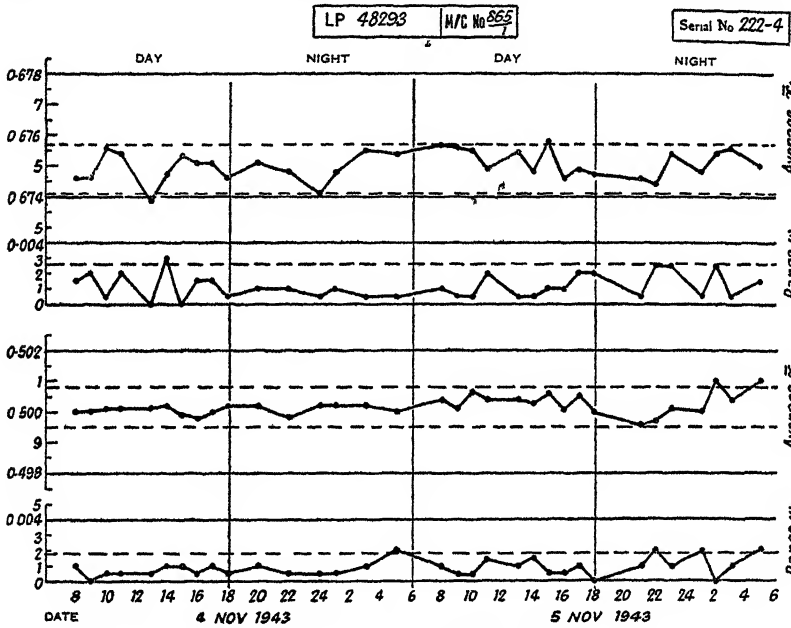


Fig. 15. Control Charts before Correction of Tool

and w for the two dimensions over a run of 48 hours. In the absence of control limits, adjustment to the press was only made when a sample average fell too close to a drawing limit. An analysis of the sampling inspection data along the lines described in connection with Tables IV and V yielded the following results :—

Dimension	*Process Average*	*Mean Sample Range*	*R.P.I.*
No. 1	0·6749″	0·0012″	3 3
No. 2	0·5002″	0·0009″	4·4

From these were calculated the several control limits indicated by the dotted lines in Fig. 15.

It will be observed, in the first place, that both sets of charts show that the process operation is reasonably well in control. In other words, once the machine is set it is capable of turning out a uniform product However, it will be noticed, secondly, that the level for dimension No. 1 is too low when that for dimension No. 2 is correct. So that any adjustment made to correct the former will automatically raise the latter and cause rejects outside the 0 502 in. drawing limit. In fact, the error of 0·0011 in. (0 6760—0·6749) in the level for dimension No. 1, added to the error of 0·0002 in. (0·5002—0·5000) in the level for dimension No. 2, gives a relative displacement of 0·0013 in. which is inherent in the punch and die, and which no amount of adjustment to the press can possibly overcome. The cause of the trouble with this particular operation becomes self-evident when one considers that such a displacement reduces the drawing tolerance—in this case by no less than one-third.*

On the evidence provided by Fig 15 the tool was sent back to the tool room for correction. Afterwards a 16-hour run with the modified tool gave values for sample average $\bar{x}$ and sample range w as shown by the charts forming the left-hand half of Fig. 16. Analysis of the sampling inspection data this time yielded the following results :—

Dimension	*Process Average*	*Mean Sample Range*	*R.P.I.*
No. 1	0·6759″	0·0015″	2·7
No. 2	0·5002″	0·0011″	3·6

Control limits were calculated afresh, using the above values of $\bar{X}$ and $\bar{w}$, and these are shown by the dotted lines in the left-hand part of Fig. 16. Here again the charts indicate stability of the production process, whilst the dimensional levels this time are quite satisfactory. In fact, the relative displacement between the two only amounts to 0 0003 in., which is but a small fraction of the allowed tolerance.

The important question that had to be settled, once the tool was properly lined up, was whether or not the production of defectives was still likely. A glance at the R P.I. values, not only for the job after correction of the tool, but also for the original operating conditions, reveals them all to be above the critical value 2·6 for the sample size $n=5$ (*cf.* Table III). Reference to Table VIII of Appendix B shows that for dimension No. 1 the R.P.I. values lie in the range of " medium relative precision," whilst for dimension No. 2 they fall in the category of " high relative precision " to be considered in the next section. Under these

* Another instructive example of this state of affairs, as revealed by control charts, is given by J. C. Edwards and W. A. Bennett in their paper on " Inspection Efficiency," *Proc. Inst. Mech. Eng*, 1945, Vol. 152, p. 69.

circumstances both dimensions can be maintained within the specified limits provided the dimensional levels (i.e., the process averages, $\bar{X}_1$ and $\bar{X}_2$) are controlled at or very close to the nominal values 0·676 in and 0·500 in.

That being the case, the job was placed under Quality Control at the end of the 16-hour run referred to above. Control limits were established for shop use, based on the values $\bar{w}_1=0\ 0015$ in. and $\bar{w}_2=0{\cdot}0011$ in. In the case of the average charts the control limits were of course located symmetrically with respect to the drawing limits. These several limits

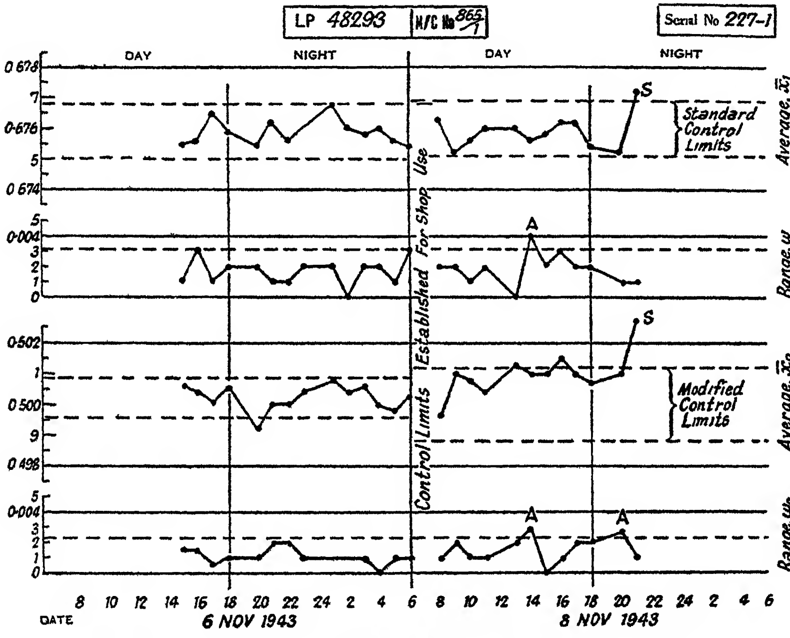


Fig. 16. Control Charts after Correction of Tool

are shown by the dotted lines in the right-hand half of Fig. 16. It will be seen that the control limits for $\bar{x}_1$ are the same as before, except that both have been shifted upwards through 0 0001 in.—the amount of displacement of the process average $\bar{X}_1$ (achieved just previously) from the aimed-at value. The control limits for $\bar{x}_2$, however, have been not only " corrected " for the corresponding displacement of 0·0002 in. in $\bar{X}_2$, but also opened out to an appreciable extent. The reason for the adoption of such wider control limits will become apparent in the next section.

The control charts for $\bar{x}$ and w, for the two dimensions, subsequent to the establishment of control limits for the press shop inspectors to work to (i.e., to use as a basis for taking corrective action), are shown at the right in Fig. 16. Points indicating lack of control—whereupon the press was adjusted—are indicated at " A " in the charts. It will be seen that an upward trend in the 0·500 in. dimension persisted throughout the day shift, but that the 0 676 in dimension remained stable. Early on during the subsequent night shift both dimensions went wildly out of control and the job was stopped for an overhaul of the set-up (indicated at " S ").

A practical example such as the foregoing brings out several features of quality control technique, not the least important of these being the technical value of information gained from the control charts (Fig. 15). Here this information enabled the production organisation (tool room, planning, etc.) to turn out a better job more quickly than they would otherwise have been able to do The very low sampling percentage (1 per cent inspection of the process) may be criticised on general grounds, but in this particular case it was the best that conditions would allow and was found to be economic as long as the production process was maintained in control

In all cases of medium relative precision it is necessary to adopt *standard* control limits, i.e., control limits calculated after the manner of Table V. Not only that, but the average chart must then be kept in control if the production of defectives is to be avoided. Where lack of control occurs, technical knowledge must be used to search for and eliminate the " assignable " causes of variation. Instability of dimensional level has its origins in such technical faults as tool wear, incorrect tool-setting, faulty machine indexing or, possibly, temperature changes and poor material (although these latter are usually associated with lack of control in the range chart).

Case (3): ***High Relative Precision.*** It is a common experience in the operation of highly accurate machine tools, such as automatic lathes (both single- and multi-spindle types) and centreless grinders, that dimensional tolerances are relatively so wide that a job can run for a very long period before defectives begin to appear, e.g., due to tool wear. In other words, the machine is really too accurate for the job in hand, but its use is justified on the score of high production rate. Thus it is the author's experience that, whereas semi-automatic machine tools such as capstan lathes and milling machines have a precision measured by a standard deviation* σ=0·0004 to 0·0010 in., the inherent precision of

* *Cf* equation (2) and the preceding discussion of the parameter σ.

automatic lathes, centreless grinders and, in some cases, presses and high-class capstans, is much greater, corresponding to a standard deviation of $\sigma = 0{\cdot}0002$ in. or even less. Under these circumstances the control chart procedures required to maintain limits of, say, $\pm 0{\cdot}002$ in. will be radically different for the two classes of machine tool in question.

To understand the modifications to the conventional quality control technique which have arisen as a practical consequence of giving consideration to cases where a machine is "too accurate for its job," let us consider an actual example of an auto operation which called for the maintenance of a recess between the dimensions 0·163 in. and 0·166 in. Rejects in this case were rarely in evidence, except due to an occasional tool failure (broken or too rapidly worn tip). With a production rate in the neighbourhood of 150 per hour a sampling inspection of 4 piece parts every $2\frac{1}{2}$ hours was decided upon when introducing Quality Control to replace the 10 per cent. gauging (inter-process) inspection hitherto employed. The first pair of control charts of Fig. 17 show the results obtained from a trial run (day-shift only) on a batch of some 12,000 piece parts. In this case the sampling inspection results were plotted for information only, and the control limits were arrived at by analysing these results at the end of the run.

The process average $\bar{X} = 0{\cdot}16424$ in. proved to be not very far off the aimed-at value of 0·1645 in., whilst the mean sample range worked out at $\bar{w} = 0{\cdot}0005$ in. The relative precision index for this particular job is thus $2T/\bar{w} = 0{\cdot}003/0{\cdot}0005 = 6$, which is far above the critical value 2·9 for the sample size $n=4$ (*cf.* Table III). Hence there is never any likelihood of defectives being produced if the sample average $\bar{x}$ is controlled within the calculated limits shown by the dotted lines on the average chart. Actually, the chart indicates very considerable lack of control. *But in a case like this it does not matter.* A little consideration will show that it is uneconomic to attempt to control the sample average within limits arrived at in the conventional manner—the so-called *standard* control limits—because to do so would involve repeated tool re-setting when in fact there is no practical reason for taking such action. In other words, to insist on such action being taken whenever a point on the average chart fell outside the standard control limits would lead, in such a case to the attempt to control the production process within narrower working limits than those laid down.

In fact, if it were possible to maintain the average chart in control with respect to the standard limits, then the production process itself would be controlled within the stability limits indicated by L_1 and L_2

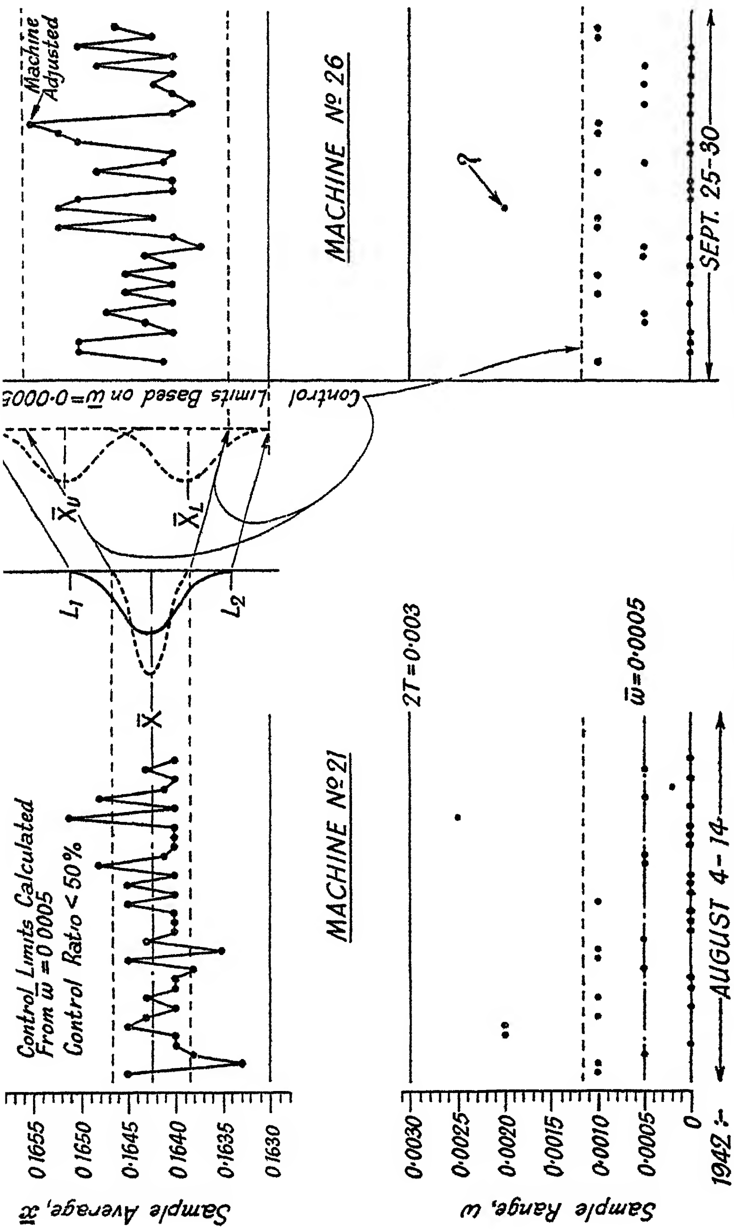


Fig. 17. Quality Control of Two Successive Batches (Auto Operation)

in the middle diagram of Fig 17.* But there is clearly no object in attempting to achieve control within such limits, for the specified working limits lie well outside L_1 and L_2. How, then, should the control limits be located on the average chart so that advantage may be taken of the wide margin between the stability limits (determined by the production process) and the drawing limits (determined by the designer)? What modifications are required in order to cater for such cases of high relative precision? The correct procedure is to set the control limits *inwards from the drawing limits* instead of, as hitherto, outwards from the process average or the nominal drawing dimension. The distance by which the control limits are set in from the drawing limits is given by $E\bar{w}$, where the factor E is found from Table VII in Appendix B.†

These widened limits on the average chart are known as *modified* control limits How they are arrived at may be seen from the diagram in the middle, and the upper control chart on the right of Fig. 17.‡ Clearly there is such a wide margin between the "natural tolerance" of the production process (i.e., the spread between the stability limits $L_1=\bar{\bar{X}}+3\sigma$ and $L_2=\bar{\bar{X}}-3\sigma$), that the process average $\bar{\bar{X}}$ may drift or wander about anywhere between a lower limit $\bar{\bar{X}}_L$ and an upper limit $\bar{\bar{X}}_U$, for which the corresponding control limits are $(\bar{\bar{X}}_L-A\bar{w})$ and $(\bar{\bar{X}}_U+A\bar{w})$ indicated by the dotted lines in the upper of the second pair of control charts in Fig. 17.

In this particular case the data yielded by the trial run of 12,000 piece parts were used to determine the control limits for shop use in "quality controlling" the later batch of piece parts, the two autos in question being identical in type and age. The inherent precision of these machines, as measured by the mean range $\bar{w}=0{\cdot}0005$ in. in samples of $n=4$ obtained from the trial run, served to determine the modified control limits—

$$\text{(Upper Drawing Limit)}-E\bar{w}=0{\cdot}166-(0{\cdot}75\times0{\cdot}0005)=0{\cdot}1656 \text{ in.}$$

and

$$\text{(Lower Drawing Limit)}+E\bar{w}=0{\cdot}163+0{\cdot}0004=0{\cdot}1634 \text{ in.}$$

in the average chart for the second batch. Only part of this, as well as

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* Under these conditions of assumed stable production the dotted curve shows the dimensional pattern (sampling distribution) of the sample averages $\bar{x}$, whilst the solid curve shows the corresponding pattern (bulk distribution) of the individual piece part dimensions x, i.e., the production characteristic.

† It can be shown that the control limit factor E is defined by $(\sqrt{n}-1)A$, where A is the corresponding factor used in determining the standard control limits for sample average $\bar{x}$. See, for example, the author's article on "Recent Developments in Quality Control," *Machinery*, 1st July, 1943, p. 16.

‡ *Cf.* also Fig. 11 (*c*).

of the corresponding range chart, are shown in Fig. 17. To be on the safe side from the point of view of anticipating possible drifts in the process average $\bar{X}$ (e g., due to tool wear), the sampling inspection was increased to 4 piece parts every hour, i.e , approximately 3 per cent. of the product was inspected under Quality Control. It will be seen that on one occasion the machine was re-set, at the end of such a trend, in time to prevent the production of defectives (piece part dimension outside the upper drawing limit).

By the use of such modified control limits on the average chart, when this is justified by a sufficiently high R P I. value for the production process, one is able to allow for a *predetermined* amount of non-random dimensional variation such as a gradual drift due to tool wear or long-period fluctuations in the process average. This amount is, of course, predetermined by the consideration that no individual piece part may have a dimension falling outside either drawing limit Where such modified control limits are used, however, it must always be borne in mind that *absence of defectives, even when the sample average is maintained in control, depends on the process variability remaining constant.* Hence it is vitally important to keep a range chart as well as the average chart ; or, at least, to keep a careful watch on the individual range values (during sampling inspection) to see that none exceeds the control limit value $D\bar{w}$. The reason for this necessity becomes clear immediately one considers the fundamentally economic character of statistical control limits.* Whether these are " standard " limits, located in the conventional manner, or " modified " limits, as determined by the method illustrated in Fig. 17, such control limits represent an economic balance with respect to the consequences of two kinds of errors, viz., looking for trouble that does not exist, and failing to look for trouble when it does exist.

In so far as all control limits are based upon a fixed value of the mean sample range $\bar{w}$, the assumption underlying their use is that the inherent precision of the production process remains constant. If, during the course of production and the period covered by the control chart, that precision falls off for any reason, so that $\bar{w}$ increases,† then in the standard type of chart the true position of the control limits for $\bar{x}$ will lie outside the fixed " action lines " drawn in advance on the control chart for shop use. For these lines ($\bar{X} \pm A\bar{w}$) were calculated from the original value of $\bar{w}$. Hence by making use of them we shall be taking action (to correct

* On this point see, for example, § 19 (*b*) on p. 16 of *B.S.*1008-1942.

† *Cf.* equation (2) and the preceding discussion of the parameter σ.

assignable causes of variation in process average $\bar{X}$) sooner, and thus more often, than we really ought to be doing under the changed circumstances. But when using modified control limits the converse is the case. Because any increase in $\bar{w}$ will augment the distance $E\bar{w}$ between these limits and the drawing limits and, as the result, the true position of the control limits will fall inside the fixed action lines drawn on the chart. In other words, when the inherent precision of the production process deteriorates there is actually less room for the process average to wander about in than there was originally, before the precision had fallen off. Hence in disregarding this effect of an increased $\bar{w}$ under such circumstances we shall be taking action (to prevent excessive variation in the process average $\bar{X}$) later, and thus less often than we ought to be doing. That is the reason why it is necessary, when using modified control limits, to keep a close watch on the sample range w. If at any time successive values of w exhibit, on the whole, an upward tendency then it may be necessary to recalculate $\bar{w}$ and to revise the control limits on both average and range charts.*

Emergency Short-cuts in Setting Control Limits. It will have been noticed that, quite apart from the use of " modified " in place of " standard " control limits, the procedure adopted in the example of Fig. 17 for setting control limits on the charts differed somewhat from that set out at the beginning of this chapter. To be specific, the control limits calculated from sampling inspection data given by one run of a job were used on a later run of the same job performed by another machine. Such a procedure is clearly a radical departure from correct practice, where the control limits are calculated from a few samples taken at the beginning of a run, and are then projected forward on the charts to serve as " action " limits for the remainder of the run.

This method of using the sampling inspection results from one batch of piece parts to set control limits for shop use on the next batch is quite legitimate, although it should be employed with discretion until experience is gained of the relative behaviour (from the quality control standpoint) of different machines, tool set-ups and operations. Nevertheless, in experienced hands this method of batch-by-batch control is valuable as a time saver, where Quality Control is introduced on a large scale, more particularly in machine shops where the runs are of relatively short duration, e.g., 20 to 30 hours. It has been conspicuously successful

* For example, in the case illustrated in Fig. 16.

in at least one precision engineering firm, where the usual batch size varies between 500 and 1,500 piece parts.*

In fact, where small-batch production is the order of the day, it is no longer a practical proposition to work out control limits after the customary manner described in connection with Tables IV and V. Because to get enough samples for this purpose the inspection interval would have to be made far too short. Otherwise the batch would be completed before one had a chance to calculate the control limits. In the circumstances one is forced to make use of the sampling inspection data of a previous batch, or of several such batches.

What about the first batch of a series? Is it possible to pre-set control limits without any prior information whatsoever? Strictly speaking, the answer is "No." But in practice we can resort to a short-cut method, *as an emergency measure*, based on the R.P.I. theory developed earlier in this chapter. The method is as follows:—

(1) *Average Chart.* Locate the control limits symmetrically with respect to the drawing limits and at a distance apart equal to the drawing tolerance multiplied by the control ratio given in Table III.

(2) *Range Chart.* Locate the control limit(s) at a distance from the zero axis equal to D (and D') times the quotient

$$\frac{\textit{Drawing Tolerance}}{\textit{Relative Precision Index}},$$

D (and D') being taken from Table VII in Appendix B, and the R.P.I. from Table III.

As a concrete example, consider the case of Fig. 17. Here the drawing limits are $0{\cdot}1645 \pm 0{\cdot}0015$ in. and the sample size is 4 (piece parts per inspection visit). The drawing tolerance is thus 0·003 in. whilst the control ratio is 0·5. Hence the control limits for sample average $\bar{x}$ would be located at $0{\cdot}1645 \pm 0{\cdot}0008$ in. Referring to Table VII, Appendix B, we find for $n=4$ that $D=2{\cdot}26$ (and $D'=0{\cdot}19$), whilst Table III gives 2·914 as the R.P.I. Consequently the control limit(s) for sample range w would be placed at 0·0023 in. (and 0·0002 in.). It so happens that in this case the above short-cut works out satisfactorily, for the actual R.P.I. of the job is well above the critical value. But where a machine is not really accurate enough for its job this rule-of-thumb method for pre-setting control limits will lead to trouble, because *it is not based in any way on machine performance* and hence cannot be properly regarded as a method of quality control at all.

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* See *Machinery*, 30th July, 1942, p. 118, and *ibid.*, 13th August, 1942, p. 169.

A question that is frequently asked by those beginning to make some progress with quality control technique is whether there is any way in which the sample size can be brought down to the irreducible minimum of one piece part per inspection visit. Cases sometimes arise where the time taken to inspect a sample of 4 or 5 piece parts for compliance with dimensional limits takes too long in comparison with the production-cycle time. Thus, to maintain a satisfactory percentage of process inspection and, at the same time, to keep the inspection interval down to a reasonable minimum, one may wish to inspect one item every half-hour, say, rather than four items every two hours. Is it possible to operate a system of quality control with the theoretical minimum size of sample, $n=1$? Here, again, the answer is "No"—strictly speaking. For a sample of only one item cannot possibly exhibit dimensional variation. Where there is only a single value of the piece part dimension, x, there is no average value, $\bar{x}$, nor range value, w. Hence the conventional control charts are no longer applicable.

There *is* a way out of this theoretical difficulty, however, by using the difference between successive sample values as a measure of process variation. In fact, we make use of the average of these successive differences to calculate control limits for both the individual sample value x and the successive difference d. The procedure is set out in Table VI and is illustrated by the control charts of Fig. 18 relating to

TABLE VI

CONTROL CHARTS FOR THE CASE WHERE $n=1$

Sample No.	Piece part Dimension x	Successive Difference d
1	1·8725″	0·0020″
2	1·8745″	0
3	45	0·0005″
4	50	5
5	45	15
- - -	- - -	- - -
23	30	45
24	75	15
25	1·8760″	0 0005″
Total	1275	340
Mean	$\bar{X}=1{\cdot}8700+\frac{0\ 1275}{25}=1{\cdot}8751''$	$\bar{d}=\frac{0\ 0340}{25}=0{\cdot}0013_6''$

a differential length dimension produced on a single-spindle (index) auto, the production-cycle time being of the order of six seconds. A

›iece part is taken from the machine every twenty minutes and measured o the nearest " half-thou." The successive dimensions obtained are ecorded in the second column of Table VI. The third column gives the orresponding successive differences. The first entry, against " Sample No. 1 " is the numerical difference between the dimensions of the first and second samples, viz., 1·8745—1 8725=0·0020 in. Similarly, the penultimate entry in that column is the dimensional difference between amples Nos. 24 and 25, viz., 1·8775—1·8760=0·0015 in. Again, the last ntry is the difference, 0·0005 in., between 1·8760 in. (No. 25) and ·8755 in. (No. 26—not shown).

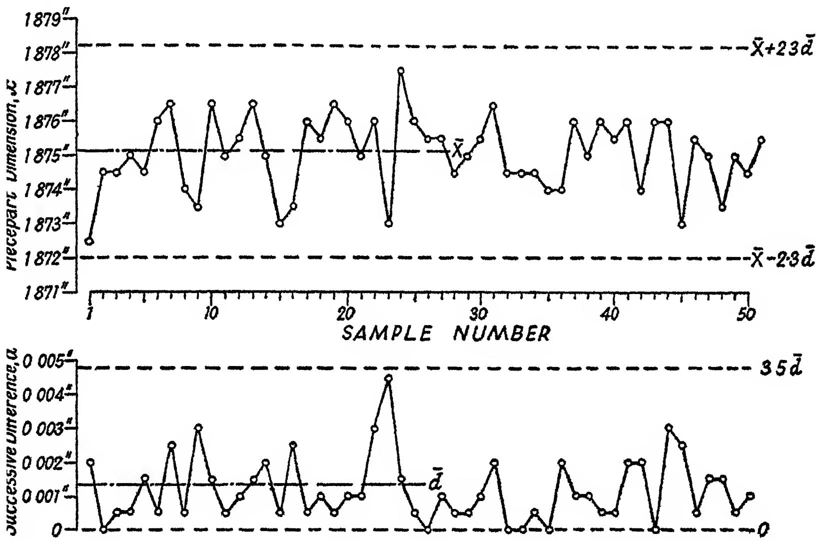

Fig. 18. CONTROL CHART METHOD BASED ON INDIVIDUAL VALUES AND SUCCESSIVE DIFFERENCES

For purposes of calculating the process average $\bar{X}$ and the mean uccessive difference $\bar{d}$ *not less than 25 sample readings should be taken,* preferably as many as 40 or 50 if possible. At the foot of Table VI is hown the arithmetical working which is in principle the same as that of Table V. The control limits are then obtained as follows :—

(*a*) *Piece Part Dimension*, x :

$$\text{Upper Limit}=\bar{X}+2{\cdot}3\bar{d}=1{\cdot}8751+(2{\cdot}3\times0{\cdot}00136)$$
$$=1{\cdot}8751+0{\cdot}0031=1{\cdot}8782\,\text{in.}$$
$$\text{Lower Limit}=\bar{X}-2{\cdot}3\bar{d}$$
$$=1{\cdot}8751-0{\cdot}0031=1{\cdot}8720\,\text{in.}$$

(*b*) *Successive Difference, d*:

Upper Limit $=3\cdot5\bar{d}=3\cdot5\times0\cdot00136=0\cdot0048$ in.

Lower Limit $=0$

These control limits for x and d are then projected forwards on the chart to serve as "action lines" for shop use, in the same way as the limits for $\bar{x}$ and w in the standard type of control chart based on sample average and range. Where as few as 25 sample values are used to calculate the limits it is advisable to revise them after a further 25 values have become available. In the example of Fig. 18 the process average and mean successive difference for the first 50 samples were found to be $\bar{X}=1\cdot8750_5$ in. and $\bar{d}=0\cdot0012$ in. Thus for the remainder of the production run the control limits were located at 1·8778 in. and 1·8723 in. on the x-chart and at 0·0042 in. on the d-chart.

A Note on Sampling Inspection Procedure. The method of taking a sample of n piece parts which has become almost standard practice in quality control work is to collect the n piece parts in succession as they come off the machine. The reason for doing so is simply that the dimensional variation exhibited by such a sample is the minimum possible for the job in question, and is a measure of the intrinsic variability (i.e., the inherent precision) of the production process. It will be recalled that this rock-bottom variability is defined by the so-called standard deviation of the production characteristic, σ ("sigma"), and that in practice it is replaced by its equivalent $\bar{w}$, the mean range found in a succession of samples of equal size n.

Hence for purposes of quality *control*, as distinct from quality *assurance*, the collection of a few piece parts in succession, to form our "sample" of individual piece part dimensions, is the only way to obtain an accurate picture (in miniature, of course) of the job's dimensional pattern at the instant of the patrol inspector's visit to the machine. On the other hand, if we are looking for an overall view of product quality, rather than for a picture of the production process, such an "instantaneous" sample is not quite so useful. Because our overall view must include the effects of all the changes in the production process which take place during the intervals between patrol visits. If the production process is unstable, that is to say, if the points in the quality control chart frequently run outside their control limits, it is fairly evident that the dimensional variation exhibited by the completed product (i.e., the batch of piece parts turned out by the production process) will be greater than that shown by our sampling inspection results. Because these results, as used in calculating control limits, imply a kind of average production characteristic

taken over the run of the job. Whereas, in fact, the finished product derives from all the many different production characteristics—differing in position or spread, or both*—which may occur as the result of the several "assignable" causes of variation discussed in Chapter III.

Hence if we require an overall view of product quality, as we may do if we wish to use our sampling inspection results to give quality assurance, the individual piece part items in the sample must be taken in such a way as to be representative, not of the state of production at a particular instant, but of all the piece parts produced since the previous sample was taken. This involves what is called "random" sampling and in practice its operation is as follows. The piece parts are allowed to collect in a bin or tray, and at the scheduled patrol visit the inspector removes it and takes from it a sample of n piece parts selected at random. Under these circumstances the dimensional variation exhibited by the sample is somewhat greater than the minimum possible for the job in question, because it is a measure of the intrinsic variability of the production process, *together with* the added variability introduced by (external) causes of process instability which may have been operating during the preceding inspection interval.

Because random sampling provides a check on all that might happen between the patrol inspector's visits to the machines, and so gives the most accurate picture of the overall quality of the work produced, it is often adopted in cases where control charts are to be used as evidence of product quality in lieu of 100 per cent. (detail) inspection at the conclusion of the production process†. This alternative sampling inspection procedure, however, does not give the best guide to the tool-setter, for he has to take action on information which is largely past history instead of up-to-date news ; neither does it give the most accurate information as to the inherent precision of the production process, for the dimensional variation in the sample is due not only to the intrinsic variability associated with the job in question, but also to such factors as tool wear, resetting, etc., during the inspection interval. In other words, *random* sampling is not a sound basis for Quality Control. The correct procedure to adopt is that which we have termed *instantaneous* sampling—the collection of the piece parts in succession as they are produced.

Some Criticisms of Quality Control. In spite of the already widespread and growing use of Quality Control in production engineering organisations

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* *Cf.* Fig. 6.

† In this connection see footnote on p. xiii.

throughout this country, and of the considerable dissemination of technical information regarding the applications of this new technique in machine shops engaged on repetition work, there still remains a certain amount of criticism of quality control methods in practical engineering circles. Much of this criticism is unfortunately misinformed and arises from a lack of understanding of the fundamental principles of Quality Control. Those steeped in the traditional methods of "direct inspection," whether using limit gauges or dial gauges, are not unnaturally inclined to be conservative and to look askance upon an inspection method which includes a systematic recording of the results as a basic element in inspection procedure. In the experience of the author, the following objections to the "statistical method" of process inspection (viz., Quality Control, properly so called) as compared with the "direct method," hallowed by tradition in the engineering sphere, are among those most commonly encountered :—

(1) Quality Control reduces the engineering limits, i.e., the working tolerance.

(2) Actual measurements must be made, which takes longer and requires more skill than using gauges.

(3) Statistics must be kept, involving time and paper.

(4) Production is slowed down by stopping jobs that are according to drawing.

(5) Overheads are increased by spending time and money in measuring parts whose dimensions are within the drawing limits.

(6) Additional expense is incurred in collecting and storing statistics which have no practical value.

Other criticisms of a more informed and thus constructive nature concern the applicability of Quality Control to really fast, high-precision, auto production (e.g., piece parts turned out in hundreds of thousands per week with less than 1 per cent. defectives) ; the difficulties arising with the simultaneous control of many dimensions ; the economics of the measurement method as compared with the method of counting defectives ; and the use of the control charts themselves as inspection records, instead of recording the inspection data separately on forms such as those discussed in Chapter VI.

Objection 1 is by far the most common and arises quite clearly from a misconception as to the relation between control limits and engineering limits. The fact that the former lie inside the latter in no way means that the production process is being controlled within narrower working limits, for these two sets of limits are not directly comparable. The control

limits apply only to the *average value* of the several measurements comprising the patrol inspector's "sample." As long as successive sample averages fall inside their control limits—the criterion of a stable process level—the corresponding *individual* measurements will fall inside certain other limits which define the inherent precision of the production process. It is these latter limits, and not the former, which are directly comparable with the tolerance or engineering limits. They are the so-called *stability limits* for the product and are, in fact, the "limits of accuracy" inherent in the production process. The point to bear in mind in interpreting the control chart (for sample averages) is, then, that *the control limits cannot be referred directly to the engineering limits*, for these two sets of limits relate to two different kinds of dimensional values. They can only be compared indirectly through the "control ratio" or, better still, the "relative precision index," discussed in Chapter III.

Objection 4 attacks the basic operational principle of the quality control chart as a means for taking corrective action *before* defectives are produced. It is likewise founded on the misconception that control limits are merely "narrower working limits," and that a point on the control chart falling inside the engineering limits thus represents a "job that is according to drawing." The objection is perhaps best met by considering an actual example. The lower diagram in Fig. 19 shows a machine-shop control chart for a certain milling operation where the piece part dimension had to be maintained within $\pm 0{\cdot}003$ in. of a nominal 0·312 in. The upper diagram depicts, by way of comparison, the actual patrol inspection results, plotted with reference to the engineering limits. The quality control routine in this case called for the measurement of a sample of four piece parts every hour ($n=4$). The control limits, established in the usual way from prior sampling inspection data, were calculated from the observed mean sample range $\bar{w}=0\ 0028$ in.

In this particular instance the tool-setter flatly refused to take the necessary corrective action until a point on the control chart either reached or went beyond the engineering limit—indicated at "A," "B" and "C" in Fig. 19—because he insisted that to do otherwise would be to "stop a job that was according to drawing." A glance at the sampling inspection record, however, immediately reveals the falsity of this view; because in every case the setter failed to prevent the production of defective piece parts, when he could easily have done so by taking action earlier as indicated by the control chart. A comparison of the upper and lower diagrams of Fig. 19 shows that whenever a sample average reaches the control limit the individual piece part dimensions have already

reached the engineering limit.* (The converse is *not* true, and thus one cannot achieve Quality Control in this sense by the use of limit gauges. To stop the job every time an individual piece part dimension reached the engineering limit would be hopelessly uneconomic) The control limits thus serve as indicators giving the latest possible instant for taking corrective action *before defective production has actually commenced.* Had the tool-setter taken heed, as he ought to have done, of the control chart

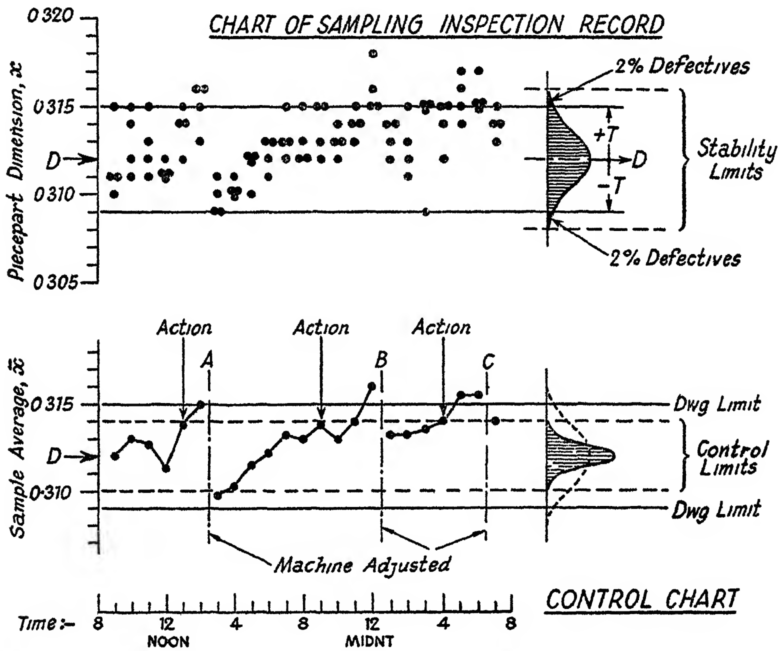


Fig. 19. Example illustrating failure to act upon indications given by Control Chart (Milling Operation)

indications he would not have had to take corrective action more often than he in fact did—production would not have been slowed up. On the contrary, it would actually have been speeded up, because the needless production of defective piece parts and their consequent sorting out from the bulk product would on all three occasions have been avoided.

The remaining misguided criticisms of quality control can be dealt with more shortly. Objections 3 and 5 are readily met by pointing out

* Incidentally, Fig. 19 shows the relation between the control limits, the engineering limits, and the " stability limits " for the production process The R.P.I. is here 2·12 so that (see Appendix C) the rate of defective production cannot be reduced below about 4 per cent.

that any system of practical and permanent value requires paper work as well as time and money spent in running it. One does not object on that score to production control or stock control systems—so why object to a quality control system? Provided such a system pays for itself by reducing scrap and rejected parts, why should it not be introduced into inspection? Surely the recent war has demonstrated to the engineering industry that the inspection department can no longer afford to be the Cinderella of the factory organisation Objection 6 may be answered by the typical examples illustrated by Figs. 12, 15, 16 and 17. There the "collecting and storing of statistics," whether in the form of sampling inspection records or control charts, or both, was shown to be of direct benefit to engineering design and production planning. Experience in this country, at any rate during the war years, has already shown the value of control charts as a reliable means of comparing one machine with another, or its present with its past performance; and as evidence, too, by which one may judge objectively between individual tool-setters, operators or groups of operators. Besides, control charts can be, and in fact have been, successfully used as evidence of product quality in lieu of subsequent 100 per cent. inspection.

Objection 2 cited above, and with it objection 5 also, is again based on a misapprehension of quality control technique. In this connection the author has seen it stated* that "one of the chief difficulties of the quality control method is that it does not permit the use of fixed limit gauges. Instead, it is necessary to use some instrument in the nature of comparator . . ." Such a statement is, of course, quite contrary to the facts of the case, for one of the simplest possible applications of quality control technique affords a practical solution to just this particular problem, viz., controlling product quality during manufacture when a measurement of individual items of product is either impossible or undesirable. This question is discussed in the next chapter.

* *Machinery*, 4th February, 1943, p. 130.

TABULAR SUMMARY OF CHAPTER IV

CASE	*No prior sampling inspection data*	*Sample range not in control*	*Sample range in control*		
Relative Precision Index	Unknown, but critical value assumed	Calculable, but not to be relied upon	Less than the critical value	Equal to the critical value	Well above the critical value
Control Limits for sample average, $\bar{x}$	Arbitrary $\bar{X} \pm T/\sqrt{n}$	Calculable, but of doubtful practical value	Standard $\bar{X} \pm A\bar{w}$	Standard $\bar{X} \pm A\bar{w}$	Modified $\bar{X} \pm (T - E\bar{w})$
Control Limits for range, w	$D\left(\dfrac{2T}{R.P.I.}\right)$	$D\bar{w}$	$D\bar{w}$ and $D'\bar{w}$	$D\bar{w}$ and $D'\bar{w}$	$D\bar{w}$
Rejections	Unpredictable	Unpredictable	Inevitable	Occasional	Unlikely
Action to be taken	Calculate $\bar{w}$ as soon as possible and obtain R.P.I.	Bring range into control	Increase either the drawing tolerance or the process precision	Maintain sample average and range in control	Particularly maintain range in control

Drawing Limits : $\bar{X} \pm T$. Aimed-at Dimension . $\bar{X}$.

CHAPTER V

CONTROL CHARTS BASED ON COUNTING DEFECTIVES

WHEN discussing the production characteristic of a manufacturing process in Chapter III, we saw that the percentage of defective product turned out by the process is measured by the area under the production characteristic lying outside the drawing limits. We also saw that, as a direct result of this unique property of the production characteristic, any change in the relative amount of defective work produced is manifested by an alteration in the position and/or spread of the characteristic with respect to the drawing limits.

Now the method of Quality Control based upon dimensional measurement enables a predetermined quality level (i e., percentage of defective product) to be maintained by taking appropriate action, as and when need for such is indicated by the control charts, to counteract any tendency of the production characteristic to change. We are here, of course, concerned with a *measurable* quality factor—length, depth, diameter, etc.—whose variation is to be controlled within prescribed limits by actual measurements carried out systematically on repeated samples of the product.

A little consideration will show, however, that an alternative means of maintaining product quality at a predetermined level presents itself in directly comparing the actual quality levels exhibited by repeated samples of the product with a chosen quality level accepted as a standard; in other words, by directly comparing the percentages of defective items found during sampling inspection with some agreed standard percentage of defective production. Needless to say, this is a far simpler approach to the problem of Quality Control than that of dimensional measurement, for it involves a mere counting of the number of defective items found in each sample of product inspected—an elementary procedure requiring no particular skill. At the same time such a method of Quality Control based on counting "defectives" has a much wider range of application, extending beyond the field of dimensional variation into the realm of quality judgments formed by visual examination of the product.

The point to note here is that we are in this case dealing with a quality characteristic which is no longer a measurable variable, but an *attribute* of the product. For example, a water tank either leaks or it doesn't—there is no half-way position. Under given tensile test conditions a piece

of steel wire either breaks under the applied load or else remains intact. In all such cases we can only assess product quality in its most elementary form, namely, in terms of the relative proportions of good and bad work actually produced. It is only to be expected, therefore, that what we gain in simplicity we lose in sensitivity. A quality control method based on counting defectives takes us back to the stage where we can at best " be wise after the event." Contrariwise, a quality control method based on dimensional measurement enables us, as we saw in Chapter IV, to " get wise before the event " There is no question but that the latter method is immeasurably superior, not only as a means of control but also as a means of gaining a valuable insight into causes of process instability. It can, under favourable conditions, actually *prevent* defective production; the other method, however, can only *reduce* defective production to some agreed minimum.

Principles and Applications. The general principles underlying the " method of defectives "—the term by which this alternative quality control procedure is generally known—are perhaps best understood by considering the case of an automatic mechanism; for example, one producing rolled threads on blank screws at a rate of several thousands per hour. Here it is a recognised experience that, no matter how perfect the design of the mechanism and no matter how carefully it is maintained, once in a while a defective screw will be produced. Defects of this kind are entirely of a chance nature and their occurrence reflects the genuinely random element of variation that is inherent in such a repetitive production process. The important point about the application of Quality Control in this case is that we cannot predict *when* these chance defects will occur, but we are able to predict *how often* they will occur in the long run. If, in fact, defective screws continue to be turned out more often than we are led to expect from considerations of chance alone, we conclude that a systematic cause of variation is present in the mechanism and hence we endeavour to search for, find and eliminate it. Having succeeded in this we are back again at the stage where defective production is due to chance causes only and is, therefore, at a minimum. That, in a nutshell, is the theory of Quality Control in so far as we are concerned with the *rate of defective production* as our quality measure.

How is this theory put into practice, say, in such a case as we have just been considering? Here also we make use of a control chart in which the " control limits " serve as indicators, pointing to the incidence of variations in the rate of defective production which can no longer be attributed to chance. After all, as we saw in Chapter III, the

technique of Quality Control is merely a scientific method of separating the random variations, due to "chance causes," from the systematic variations, due to "assignable causes." The former are, in the nature of things, beyond our control; but the latter, in so far as they can be assigned to specific physical elements in the production process (e.g., tool-setting, machine loading and operating, wear and tear, etc.), are susceptible to control. As always, the control chart is simply a device that shows us at a glance when these unwanted assignable causes of variation are present in the production process alongside the inevitable chance causes.

Before discussing the procedure for constructing quality control charts based on counting defectives, it will be as well to consider briefly the situations in which this method of quality control is appropriate and to indicate the types of control charts most suited to machine-shop applications of the method. In the first place it must be emphasised that methods of Quality Control based on measurement are quite valueless in the case of purely manual production processes, such as centre-lathe turning, grinding, coil winding and so on. Here the piece part dimension produced is entirely under the operator's control, and the operator's skill (or quality efficiency) is accordingly assessed not by the dimensional pattern of the product, but by the quantity of piece parts whose dimensions fall inside the limits laid down by the designer. The greater this quantity, the higher is the quality of the product. Here is a clear case where Quality Control by the method of defectives is the appropriate control procedure. As we shall see in Chapter VI, the control chart in this case lends itself to the introduction of a quality bonus system so as to ensure the maximum level of skill among a number of operators.

While Quality Control based on measurement is inappropriate to manual production processes it must not be thought that Quality Control based on counting defectives is equally inappropriate to automatic or semi-automatic processes. Here the question is not one of principle but of economy. Every piece part dimension *can* be measured—even a small bore or an internal screw thread. But to do so as a matter of routine, for purposes of Quality Control, may very well entail a prohibitive amount of inspection and cost. The same is true for complicated piece parts, involving the checking of a multiplicity of what are in themselves straightforward dimensions (e.g., lengths and diameters). In certain phases of component production, for example, a piece part may have half a dozen or more critical dimensions, all equally important, and it would

be quite uneconomic—except perhaps in isolated instances—to maintain control charts for each dimension. In all such situations the method of defectives offers a convenient and economic alternative to the measurement method of Quality Control.

Finally, there remains the sphere of visual inspection—the judgment of colour, finish or general workmanship Such quality judgments are notoriously difficult and yet they may be quite as important as the more or less mechanical judgment of dimensional variation. Here the introduction of control-chart methods can lead to a raising of the general level of inspection efficiency. In particular, control charts for per cent. defective may be valuable in comparing the aptitudes and efficiencies of inspection operatives engaged on a 100 per cent. visual check of mass-produced material Assuming the general quality level of the product to remain reasonably constant over a period, the efficient operatives will tend consistently to find more defectives than their less skilled or conscientious colleagues The relative merits of a number of such inspection operatives can then be assessed objectively in terms of their corresponding control charts.

A Simple Control Chart. An elementary type of control chart developed by the author in 1940 and illustrated in Fig. 20 has proved helpful in at least one machine shop, more particularly in the case of processes which habitually produce a high percentage of defectives.* The control chart is printed on a standard form and is based on a " maximum limit " of 5 per cent. defective and a " control limit " of 3 per cent. defective, the former appearing as a full line with a 5 per cent. slope and the latter as a dotted line with a 3 per cent. slope. Each horizontal division of the chart represents the end of an inspection interval, when the patrol inspector visits the machine and gauges a fixed number of piece parts taken from among the last to have been produced. A standard sample size of 10 piece parts was chosen, and the *accumulated* number of parts inspected is indicated by the horizontal scale of the chart. Similarly, the vertical scale of the control chart shows the *accumulated* number of defective piece parts found in all the samples inspected up to and including the current patrol visit.

The two charts of Fig. 20 relate to two successive batches of small gears produced by the same operator on the same machine. Initially, a sampling inspection routine of 5 per half-hour was introduced which was later altered to 10 per hour, corresponding to the standard sample size, $n=10$, for the method of defectives in this particular machine shop.

* *Cf. Machinery*, 13th August, 1942, p. 169.

Referring to Fig. 20(*a*), for example, no defectives were found in the first five samples, but at the sixth patrol visit one piece part in the sample of five was found to be defective. Thereafter, during the next eight patrol visits, no further defectives were found. At the inspector's fifteenth visit to the machine, however, two out of the five piece parts in the sample were found to be defective, making three in all, for which the corresponding point on the control chart fell outside the control limit. Appropriate action was immediately taken to remedy the sudden increase in the rate of defective production, after which the job was allowed to proceed. As will be seen from the control chart, the line joining the origin to the last

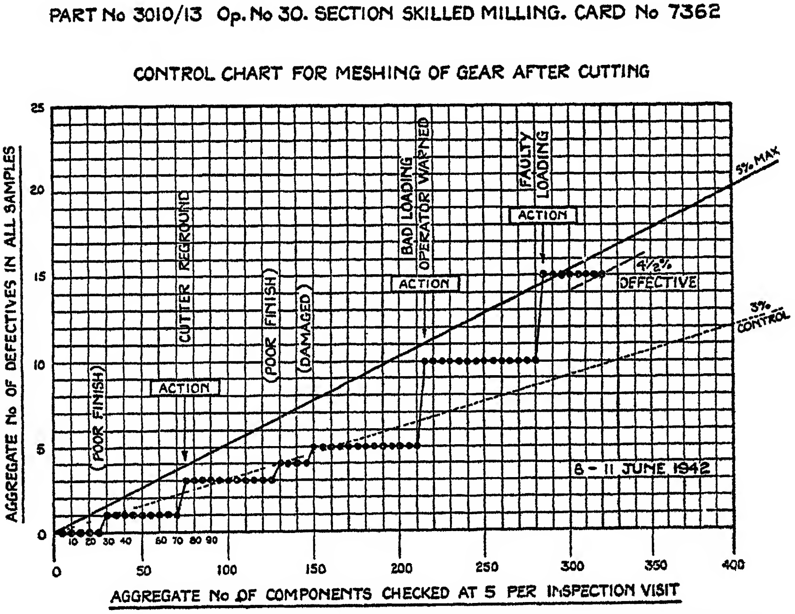


Fig. 20*a*. CONTROL CHART FOR "ACCUMULATED NUMBER DEFECTIVE"

plotted point has a slope of 4½ per cent., a value just below the limiting figure which could be tolerated for this particular product. As the 64 samples inspected during the run of the batch comprised some 30 per cent. of the total production, this sample figure of 4½ per cent. is a fair estimate of the per cent. of defectives in the batch when it reached the assembly line. The improvement in product quality obtained with the next batch of gears, as the result of the previous experience and its

control-chart record, is well illustrated by the companion control chart depicted in Fig 20(*b*).

The merit of this "cumulative" type of control chart is that it automatically furnishes an overall picture of the rate of defective production, that is, of the very quality characteristic which it is desired to control. Being of an empirical character, it is not sensitive to momentary deteriorations in product quality except at the beginning of a production run. Moreover, it is altogether too coarse an instrument of control for applications where a high quality level is desired, of the order of 1 per cent.

PART No 3010/13 Op. No 30. SECTION SKILLED MILLING. CARD No 8159

CONTROL CHART FOR MESHING OF GEAR AFTER CUTTING.

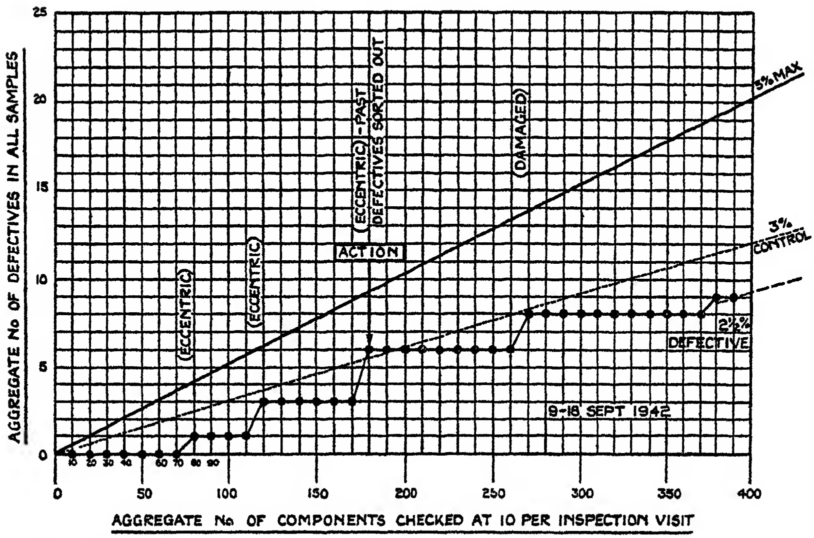


Fig. 20*b*. CONTROL CHART FOR "ACCUMULATED NUMBER DEFECTIVE"

defective. A recent development of this "cumulative" type of chart has to a large extent overcome these inherent weaknesses and made the method suitable for purposes of quality supervision (e.g., control charts for test results), if not of quality control under conditions of machine-shop production.* This improvement consists in providing a relatively simple

* This latest development is due to A. E. Worley, of the Western Regional Administration of the Ministry of Supply, and was discussed at the second meeting of the Industrial Applications Section of the Royal Statistical Society held on 19th February, 1943. (See *Report No. W*/42/158 of the Western Regional Administration, M. of S., circulated on 8th December, 1942.)

means of setting control limits, on a statistical instead of on an empirical basis, about the sloping line representing either the aimed-at or the achieved level of control, thereby making the sensitivity of the control chart uniform throughout its entire length.

Under machine-shop conditions, however, a control chart must be of such a character as to draw immediate attention to any sudden deterioration in product quality. Here the assessment of the *amount* of the change in the rate of defective production is clearly of secondary importance; it is sufficient to know that the change is a real and not an apparent one. In other words, it is more important to be able to take action quickly, where a definite need for this is indicated by the control chart, than to be presented with an overall picture of the varying rate of defective production during the period covered by the chart. The form of chart which meets these requirements is that in which the fraction, percentage, or number defective *in each individual sample* is plotted in succession, rather than the corresponding sample aggregate (as in Fig. 20). This form of control chart has become standard for quality control applications using the method of defectives.

The Standard Control Chart for Percentage Defective. In Chapter III we had occasion to refer to the Normal Law of random variation underlying the production characteristic of a manufacturing process. This statistical law applies to measurable quantities, such as tensile strength, dimension, weight, time, etc., and expresses the relationship between particular values and the relative frequencies with which they occur. It will be recalled that it is through knowledge of this law, with which mathematical statisticians have in the past provided us, that we are enabled to calculate "stability limits" for a production process, and "control limits" for sample averages and ranges as required in quality control by the method of dimensional measurement.

When considering the occurrence of defective items of product—commonly termed "defectives"—we are no longer concerned with a dimensional pattern, however, but with a quality pattern of a more general character. On the assumption that under stable conditions of production such defectives are due to chance causes, they are to be regarded as random events obeying a statistical law of variation and forming a characteristic time pattern. This law of random variation, which expresses the chance nature of rare events, is known as the Law of Small Numbers, and its projection in time leads to a frequency pattern of "occurrences" whose properties are as well established as those of the frequency pattern

described by the Normal Law.* In particular, it enables us to calculate control limits for the percentage of defectives occurring in repeated samples. For example, if under stable conditions of production we expect to find that, say, 1 per cent of the piece parts turned out by a certain process operation will fail to pass the appropriate limit gauges, then we are able to specify limits within which the corresponding percentage of such defectives found in a sample of, say, 100 piece parts should lie *if the rate of defective production remains* 1 *per cent.*

This last statement may seem strange at first sight. If samples of 100 piece parts are selected at random from a bulk known to contain 1 per cent. defectives, it is fairly obvious that in the long run an average of one defective piece part will be found per sample But this is only true on the average and in the long run It is not reasonable to expect to find one defective piece part in *every* sample of 100. A large proportion of samples will contain one defective, it is true; but an almost equal proportion will contain none. Quite a number of samples will be found to contain two defective piece parts, whilst not a few will show as many as three defectives. Moreover, one may now and again get a sample containing no fewer than four defective piece parts.

The point to note here is that in repeated sampling from a 1 per cent. defective bulk we should expect, with a sample size of $n=100$, as wide a range of variation as zero to 4 per cent. defective in the samples. This is a matter of common experience and of the " luck of the draw." Before we can be practically certain that the rate of defective production has deteriorated beyond 1 per cent., we should have to find as many as five defective piece parts in a sample of 100. Such a conclusion is by no means obvious to anyone not familiar with the statistical laws of sampling fluctuations. Most engineers, when encountering a sequence of, say, 0, 1, 1, 2, 1, 0, 1, 2, 0, 1 defectives in ten successive samples and then suddenly finding four defectives in the eleventh sample, would almost immediately conclude that a real change for the worse had taken place in the quality of the bulk product being sampled. In point of fact, however, the change is only an apparent one, for such a deviation from the long-run average of 1 per cent. defective in the samples is quite consistent with a stable quality level for the bulk.

The foregoing consideration can be expressed graphically in a very simple manner by means of the standard control chart for percentage

* For a non-mathematical account of this statistical theory of rare events as applied to accident prevention see the author's article entitled " Accident Statistics and Probability Theory " which appeared in the *BEAMA Journal,* February, 1943, pp. 38-42.

defective, an example of which is given in the lower half of Fig 21. With a sampling procedure based on patrol inspection as described in Chapter III, we shall assume that at the end of the appropriate inspection interval the last 100 screws turned out by a thread rolling machine are

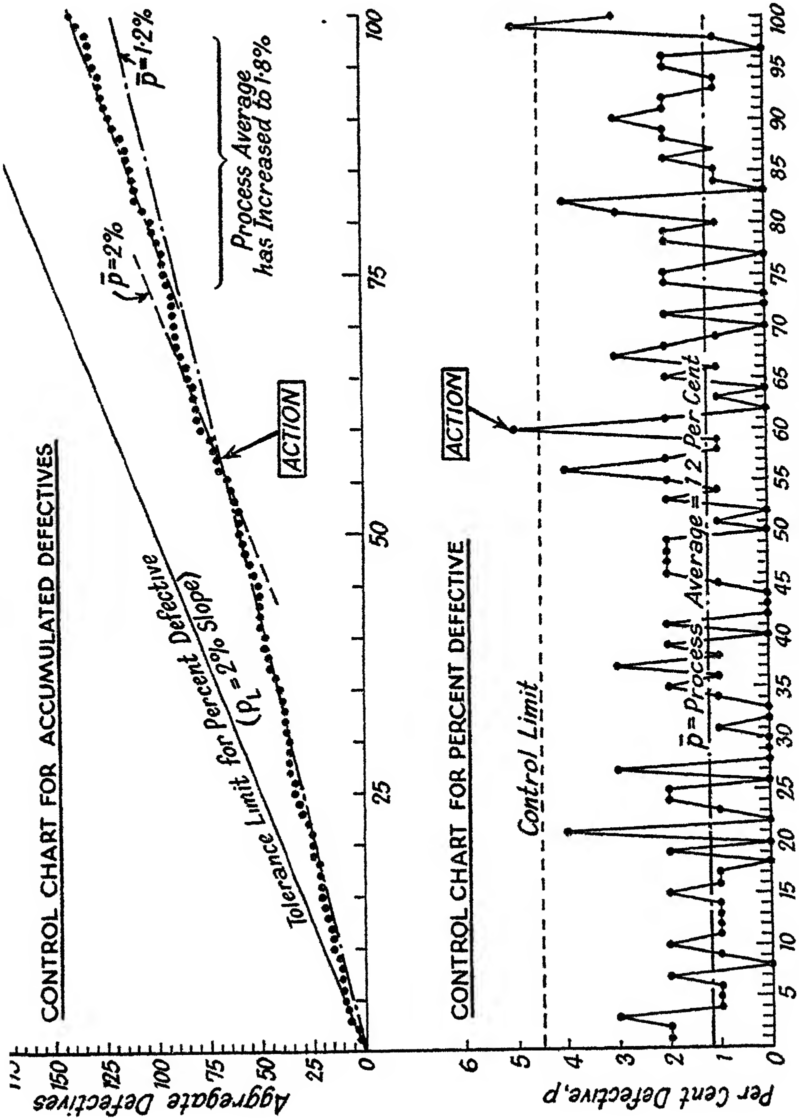


Fig. 21. Quality Control—Method of Defectives

collected and visually or otherwise examined for defective threads. Let us assume, furthermore, that the assembly shop using these screws is prepared to accept up to a maximum of 2 per cent. defectives in the bulk. The number of defective screws found in each sample of 100 is then recorded against the time at which the sample is collected from the machine, and also plotted on the chart. The vertical scale of the control chart—shown at the bottom of Fig 21—is in per cent. defective, p, which in this particular case is the same as number defective, c, since the sample size is $n=100$. In general we have .—

$$\text{Per cent. defective}=p=\frac{100c}{n}=\frac{\text{Number defective}}{\text{Sample size}}\times 100 \qquad \ldots\ldots(5)$$

The horizontal scale of the chart is really a time scale, each plotted point corresponding to one of the regular visits to the machine by the patrol inspector. In Fig. 21, however, the successive visits are conveniently indicated by a sample number sequence.

After the first 15 to 20 sampling results have been recorded and plotted, the control level or process average per cent. defective, $\bar{p}$, must be calculated from the sampling inspection data. This average rate of defective production, as estimated from the defectives found in a number of samples, is given by :

$$\bar{p}=\frac{100\bar{c}}{n}=\frac{100}{n}\times\frac{\text{Total number of defectives found}}{\text{Total number of } \textit{samples} \text{ collected}}$$

$$=\frac{\text{Total number of defectives found}}{\text{Total number of } \textit{piece parts} \text{ inspected}}\times 100 \qquad \ldots\ldots\ldots\ldots(6)$$

In the example of Fig. 21 sampling inspection data obtained previously gave a total of 19 defective screws in 16 samples of 100 taken at hourly intervals throughout two shifts, so that the process average in accordance with equation (6) is

$$\bar{p}=\frac{100\times 19}{1600}=1\cdot 2 \text{ per cent.}$$

and this value then becomes the *control level* for the chart. Next we must determine the *control limits* within which the values of p for samples of $n=100$ will lie if the rate of defective production is maintained indefinitely at the level $\bar{p}=1\cdot 2$ per cent. By referring to Chart I in Appendix B, we read off these limits for number defective, c, against the expected number of defectives per sample, $\bar{c}=19/16=1\cdot 2$*. The values are $c=4\cdot 5$ and $c=0$ for the upper and lower control limits respectively. (It should be remem-

* In this particular case, with $n=100$, c is numerically equal to p, as is at once evident from equation (5). Hence the control level for number defective, $\bar{c}$, is numerically the same as the control level for percentage defective, $\bar{p}$.

bered that numbers such as $\bar{c}=1\cdot2$ and $c=4\cdot5$ are purely theoretical figures. Actually the number defective c, since it is the count of the defective items in a sample, can only be a whole number.) Since the lower limit is zero it coincides with the base line of the chart in Fig. 21, whilst the upper limit is indicated by the dotted line drawn through the value $p=4\cdot5$. Thus, provided the rate of defective production for the process in question does not increase appreciably beyond the basic level of 1·2 per cent., no sample (of 100 piece parts) should contain more than $p=4\cdot5$ per cent. defectives, corresponding to the theoretical number defective, $c=pn=4\cdot5$ It will be observed from Fig. 21 that the 60th sample contained $c=5$ defectives ($p=5$ per cent). This occurrence is a sufficient indication of a significant deterioration in product quality and would normally call for action to be taken to remove the assignable cause of the increased rate of defective production.

The same thing occurs at the 99th sample and, on comparing the patterns of the dots on the chart before and after the 60th sample, it would seem that, on the whole, a slight upward shift in the dots had taken place. But this shift is not easy to discern and can only be established by counting the aggregate number of defectives in the two regions, dividing by the corresponding number of samples, and thus arriving at the process average ($\bar{c}$ or $\bar{p}$) before and after the 60th sample.* The cumulative chart for this example, illustrated in the upper half of Fig. 21, on the other hand, shows this deterioration in product quality very clearly. From about the 70th sample onwards the process average maintains a fairly steady level of 1·8 per cent. defective, as may be seen by the steeper slope of the line drawn through the last 28 points. A comparison of the two charts in the region of the 60th sample is equally instructive. From the point of view of taking action to improve the process, the "instantaneous" chart gives a decisive indication whereas the "cumulative" chart hardly shows any cause for action—at least not until about the 70th sample. The line drawn through the 55th sample, with the limiting slope $p_L=2$ per cent. defective, does seem to indicate a real deterioration in product quality at the 60th sample, but the indication is by no means decisive.

The foregoing example serves to make clear the superiority, for purposes of quality *control*, of the conventional type of control chart for fraction or number defective over the cumulative type of chart, which is appropriate more to quality *supervision*.

* The statistical method of treating this comparison is discussed very fully on pp. 17-20 of *B.S.*600*R*-1942 (*Quality Control Charts*).

Some Practical Illustrations. Fig. 22 illustrates the application of the foregoing procedure to the quality control of an auto job in which inspection was carried out by means of ordinary " go " and "not go " gauges. Here the economic level of control (rate of defective production) was taken as 4 per cent. defective, and the number defective (c) rather than the percentage defective (p) in the sample was chosen as the quality indicator. In view of the high production rate and the critical nature of the dimensions to be controlled, the very short inspection interval of five minutes was laid down and the sample size was fixed at the lowest

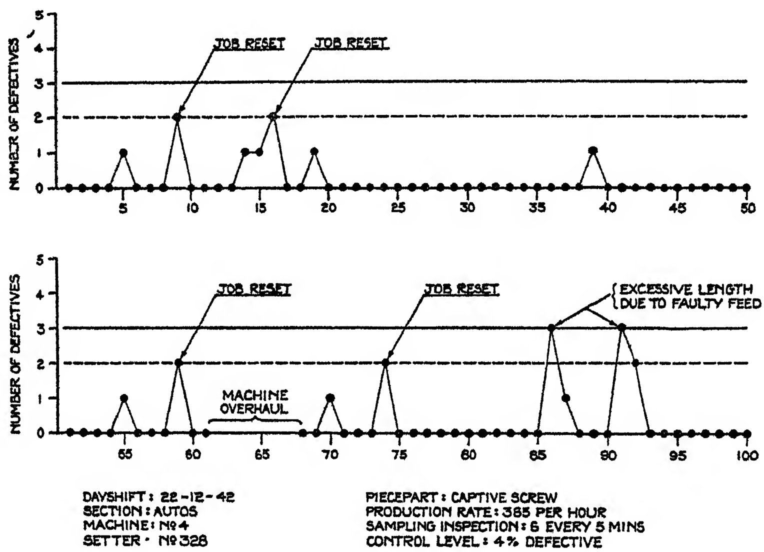


Fig. 22. Control Chart for Number Defective (Auto Operation)

possible value commensurate with a reasonable hope of finding defectives, viz., $n=6$. The expected number of defectives per sample, i.e., the control level for number defective c, is thus

$$\bar{c}=\frac{n\bar{p}}{100}=\frac{6\times 4}{100}=0{\cdot}24$$

As this value is considerably less than unity, the use of two control limits becomes advisable for reasons which need not be gone into here*. The

* *British Standard* 600*R*-1942 makes use of these two sets of limits throughout Section 4, which deals very fully with the theory of Quality Control based on counting defectives, and with the control chart for number defective On this point see also *American War Standard* Z1.3-1942, p. 19, and footnote on p. 12. (This latter publication is obtainable through the British Standards Institution.)

inner limit is then employed as a "warning" limit and the outer limit as an "action" limit. Referring to Chart II of Appendix B, we obtain the control limit values $c=2$ and $c=3$ (approximately) corresponding to the control level $\bar{c}=0{\cdot}24$ The quality control procedure in such a case is then as follows ·

As soon as a plotted point falls on the "warning" limit, indicated by the dotted line in Fig. 22, the patrol inspector immediately takes a further sample of six piece parts from the machine. If this check sample also contains two (or more) defectives the job is stopped and the tool-setter called in to make adjustments to the machine in accordance with the nature of the defectives found. On the other hand, if the check sample is found to contain less than two defectives, the job is allowed to run. If a plotted point reaches the "action" limit, indicated by the solid line in Fig. 22, the job is stopped at once, without the patrol inspector having to take a check sample. The achieved process average quality, in terms of per cent. defective, can readily be determined from the control chart or the accompanying sampling inspection record. A count of the number of defective piece parts actually found during the 8-hour run covered by the chart of Fig. 22 gives a total of 24 defectives in 93 samples of 6 The achieved process average as given by Equation (6) is thus

$$\bar{p}=\frac{100}{6}\times\frac{24}{93}=\frac{400}{93}=4{\cdot}3 \text{ per cent.}$$

which is in close agreement with the aimed-at quality level.

A practical question which arises from a consideration of the above example is that of the procedure to be adopted in the case of multi-dimensional process operations on piece parts turned out by fast production processes (e.g., power presses or multi-spindle autos).* Undoubtedly the best method to follow here is to maintain a control chart for number defective and to assign code letters to the different dimensions to be controlled. Whenever a plotted point reaches either the warning or the action limit, the dimensions responsible for the defectives in the sample should be noted and the corresponding code letters placed alongside the point on the chart. In this way the repeated occurrence of a particular code letter throughout the chart will enable the assignable cause of faulty production to be tied down to a particular dimension. A control chart for averages $\bar{x}$ (and, possibly, also for ranges w) should then be maintained for this troublesome dimension, when the fault may be tracked down and remedied. This method of procedure is simple to apply, and has in certain cases yielded very valuable results.

* Control charts based on measurement would be clearly uneconomical of inspection effort.

At least one engineering firm in this country has elaborated a procedure of this kind to cover as many as fifteen dimensions and visual defects simultaneously.* An example taken from another engineering organisation is illustrated in Fig. 23 and relates to a series of machining operations on a hank bush performed by an indexing auto. Here the number of defectives found in each sample is still plotted on the vertical scale, but at the top of the chart a simple and convenient analysis of the cause of rejection is given. The dimensions controlled by the various gauges are indicated in the column headed "Reason for Rejection," each reject classification being subdivided into "oversize" and "undersize" as indicated by the letters "O" and "U" respectively The control level in this case was fixed at 4 per cent. defective and samples of ten piece parts were gauged at 15-minute intervals. Here $\bar{c} = 0{\cdot}4$ and the corresponding control limits were located at $c=2$ and $c=4$ (The theoretical values given by Chart II of Appendix B are 2·5 and 3·8.) Check samples taken immediately after the occurrence of two defectives in the 7th and 19th samples in both cases showed no defectives, but the occurrence of five defectives in the 11th sample was sufficient evidence that the set-up required overhaul and an adjustment was accordingly made. It would appear that this adjustment for oversize diameter adversely affected the counterboring operation as all but one of the subsequent rejections were for undersize of the depth of counterbore. Here is a case where a planning investigation might be worth while, although the achieved process average,

$$\bar{p}=\frac{100}{10}\times\frac{13}{34}=3{\cdot}8 \text{ per cent.},$$

is within the specified quality limit of 4 per cent. defective. At any rate, the maintenance of dimensional control charts for the 0·280 in. diameter and the depth of counterbore would very soon reveal whether the existing tooling of the job was productive of a correlation between these two dimensions.

Another question that arises immediately in the minds of those familiar with machine-shop practice is: How does one apply such a control chart in cases where the control level is effectively zero ? In other words, how can the method of defectives be used to control quality when no defective piece parts are permitted to pass through the sieve of sampling inspection ? Taken literally, of course, the answer is that it can't be done. But if an occasional defective piece part may be allowed

* *Vide* W. A. Bennett and J. W. Rodgers: "Quality Control" (*Aircraft Production*, 1943, Vol. 54, pp. 172-175).

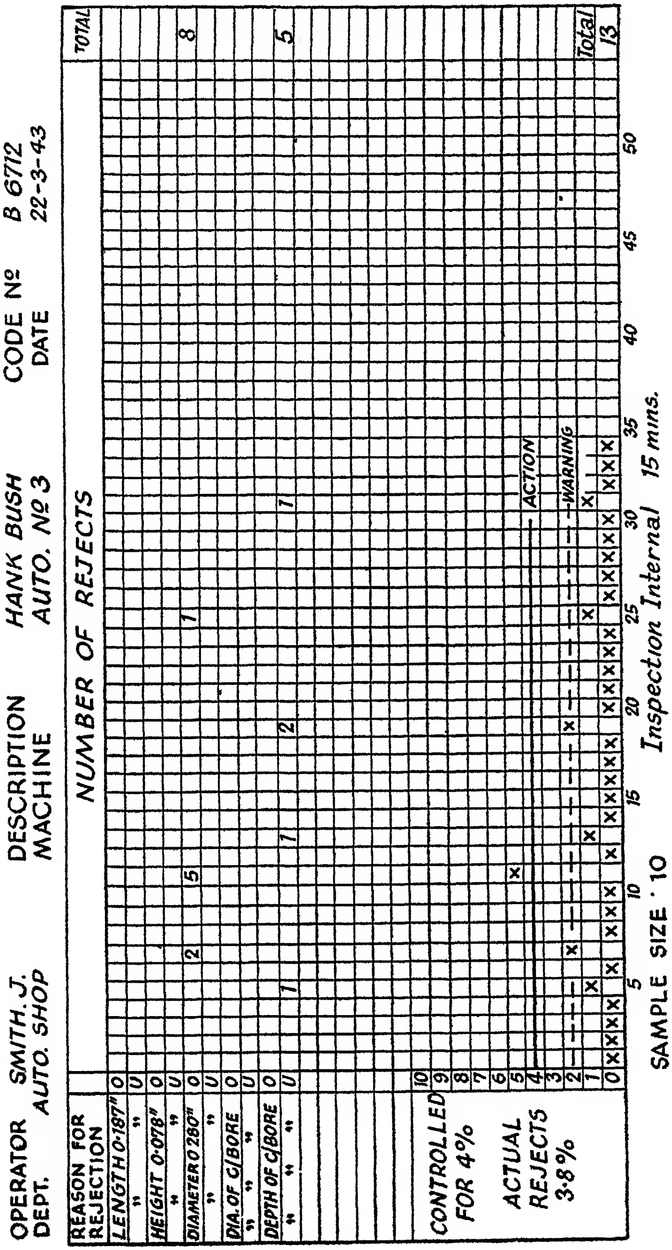
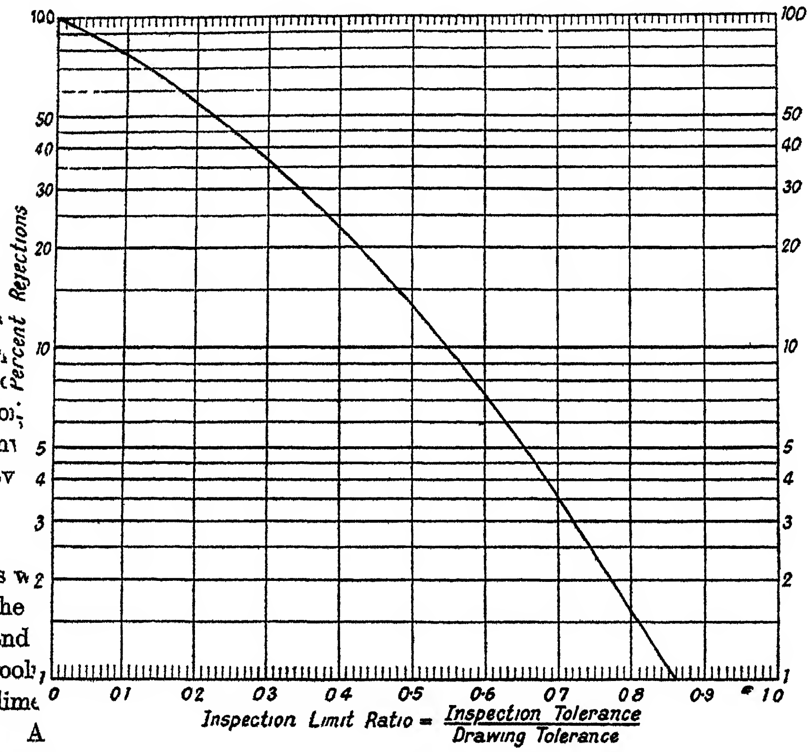


Fig. 23. Multi-dimensional Control Chart (Control Level: 4 per cent)

to slip through, after allowing for the sorting out of any defectives produced during the "unstable" inspection intervals, a practical way out of the difficulty of a zero control level is to use inspection gauges set to narrower limits than the drawing limits. Such a procedure will artificially inflate the control level to a figure enabling the sample size to be kept down to a small value. In general an "inflated" control level of $\bar{p}$=5 to 10 per cent. defective will be found adequate for quality control along the



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...4. RELATION BETWEEN INSPECTION LIMIT RATIO AND ARTIFICIAL CONTROL LEVEL $\bar{p}$

...lescribed in connection with Fig 21. The author has termed the ...f inspection tolerance to drawing tolerance—a concept appropriate ... extension of the method of defectives—the *inspection limit ratio*, ... relation between this ratio and the fictitious control level (to ...ained by the use of the inspection gauges) is given by Fig. 24. ...nption underlying this relationship is the practical one that the

* *Vide* ... *tion*, 1943,

percentage of piece parts whose dimensions fall outside the drawing limits (i.e., the true percentage defective) shall be effectively zero, irrespective of the percentage failing to pass the inspection gauge (i e., the percentage rejection).

For example, let us assume we want to use a control chart for number (or percentage) defective to maintain a certain dimension, say, a 0·625 in. length, within limits of $\pm$0·002 in. By making our inspection gauge with a "go" limit of 0·626 in. and a "not go" limit of 0 624 in. we should be working with an inspection limit ratio of 0 5. Provided the machine in question, when performing this particular operation, is capable of meeting the drawing limits, then our inspection gauge should not throw out more than about 13 per cent. of the product. With a sample size $n=10$, say, the expected number rejected by the inspection gauge would be $\bar{c}=1{\cdot}3$ Referring to Chart I of Appendix B, the corresponding control limits become $c=5{\cdot}5$ and $c=0$. Thus if we get a sample in which 5 or 6 piece parts are rejected by the inspection gauge we can be pretty certain that the process is tending to produce work that is outside the drawing limits.

Unfortunately, this method of using a control chart based on "rejects" instead of defectives, properly so called, is of little value in cases where the machine is too accurate for its job. Suppose the machine in question could hold limits of $\pm$0·001 in. and that the tool-setter adjusted it so that all the product fell within the range 0·625 in. to 0·627 in. In that case 50 per cent. of the product would be rejected by the "go" gauge. Conversely, if the machine were set to produce every piece part within the range 0 624 in. to 0·625 in., the 50 per cent. of the product would be rejected by the "not go" gauge. But if the tool-setting were such that only dimensions between 0·624 in. and 0·626 in. were being turned out, then no product at all would be rejected by the inspection gauge. In none of these three cases would any product be made outside the drawing limits 0·625 in. $\pm$0 002 in. Yet the rejection level of our inspection gauge might be anywhere between zero and 50 per cent., depending on the tool-setting. So that to base a control chart on the calculated level of 13 per cent. rejection (as found from Fig. 24) would be worse than useless.

The real answer to the question of preventing, as distinct from minimising, defective production is, of course, to use control charts based on dimensional measurement. Because then, and only then, does one obtain full information about the production characteristic of the process. Without such information it is impossible to say whether the production

of defectives is inevitable or not. However, a compromise may be effected by using inspection gauges set to limits, closer than the drawing limits, which are calculated from consideration of the inherent precision of the process. Fig. 24 presents this calculation in the form of a simple graph for the specific case where the production process is just capable of meeting the drawing limits, i e. where the stability limits $\bar{X} \pm 3\sigma$ coincide with the drawing limits $D \pm T$, as depicted in Fig. 11(b). The general case of low relative precision, illustrated in Fig. 11(a), clearly does not call for the use of special inspection gauges at all, because the drawing limits are already being exceeded, so that the ordinary shop gauges set to these limits will reject true defectives. It is the other general case, that of high relative precision, shown in Fig. 11(c), which, as already explained, requires especial consideration.

It would be exceeding the scope of the present work to give the theory underlying the calculation of the inspection limits for this important case. Sufficient be it to state that the optimum value of "percentage rejection" by such gauges is around $\bar{p}=10$ per cent. Under these circumstances the required Inspection Limit Ratio is given by :—

$$\text{I.L.R.} = 1 - \frac{9}{20}\,\frac{(\text{Critical R.P.I.})}{(\text{Actual R.P.I.})} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where the critical value of the Relative Precision Index is taken from Table III on p 45. As a practical illustration of the use of the above formula let us again consider the case of a simple parting-off operation to give a specified length of $0{\cdot}625 \pm 0{\cdot}002$ in., and let us assume that a sample size of $n=10$ is decided upon so as to get an expected number rejected (by the inspection gauges) of $\bar{c}=\bar{p}n/100=1$ per sample, approximately. Here the drawing tolerance is 0·004 and the critical R.P.I. value is 1·95. Moreover, we shall assume also that over a test period of sampling inspection, based on the methods described in Chapter IV, the sample measurements yielded a mean range of $\bar{w}=0{\cdot}00091$ in. The corresponding R.P.I. value is $2T/\bar{w}=0{\cdot}004/0{\cdot}00091=4{\cdot}4$, so that the required inspection limit ratio is found to be :—

$$\text{I.L.R.} = 1 - \left(\frac{9}{20} \times \frac{1{\cdot}95}{4{\cdot}4}\right) = 1 - \left(\frac{17{\cdot}55}{88}\right) = 0{\cdot}8$$

Hence the inspection tolerance is 80 per cent. of the drawing tolerance, and the inspection gauges must accordingly be set at $0{\cdot}625 \pm 0{\cdot}0016$ in. Using these gauges we would obtain a control chart of the kind illustrated by Fig 22 in which, to begin with, we should draw our control limit at $c=4$ corresponding to the assumed process average, or control level, $\bar{c}=1$ (see Chart I of Appendix C). As soon as some 15 to 20 points had

been plotted, and providing in that period no sample of 10 had given as many as 4 rejections, the estimated control level should be revised, using equation (6) to find the actual rate of rejection, $\bar{p}$, and a new control limit should be drawn in and carried forward on the chart based on the corresponding revised value of the average number rejected per sample, $\bar{c}$.

The Two-way Control Chart. A refinement of the simple type of control chart for percentage (or number) defective discussed so far is the so-called "two-way" control chart. Its use involves a subdivision of the defectives into the two categories "high" and "low," i.e., a separation of defective product into items which fail to pass the "go" gauge and those which fail to pass the "not go" gauge. A pair of control charts is then maintained, one for each class of defectives. Fig. 25 shows such a dual control chart for a trimming machine where the quality of the finished piece part is almost completely in the hands of the operator. Although with care and attention an extremely low rate of defective production can be maintained, quality can easily deteriorate with carelessness or lack of skill. Although the hand lever on the machine is brought to a fixed stop, this in itself will not guarantee a piece part being kept within the specified dimensional limits. Too much pressure on the lever after it has reached the stop will cause the parts to be undersize; too light or too quick a pressure will make them oversize. Again, too fast a cutting feed may cause a fragile part to spin on the fixture and be damaged, whilst too slow a feed leads to the collection of so much swarf that the body sides get scored and the part is rejected on that account.

In this particular case the production rate was 2,000 per hour, and samples of 60 were collected every half hour and checked by "go" and "not go" gauges. The control level for the "go" gauge had to be fixed at 2 per cent. defective, but in the case of the "not go" gauge the situation was not so critical, and a control level of 5 per cent. defective was decided upon as being economic. Accordingly the expected numbers defective per sample were $\bar{c}_1=0{\cdot}02\times60=1{\cdot}2$ for the "go" gauge and $\bar{c}_2=0{\cdot}05\times60=3{\cdot}0$ for the "not go" gauge. It so happens that the machine shop in question habitually made use of both "warning" and "action" limits in all their control charts*, so that the appropriate control limits are to be taken from Chart II of Appendix B. We there find for the action limits $c_1=6$ and $c_2=10$, and for the warning limits $c_1=4$ and $c_2=7$. These limits are shown on Fig. 25 as solid and dotted

* This is the practice recommended in *B.S.*600*R*-1942 It is a moot point whether warning limits are worth while in the case of quality control by dimensional measurement.

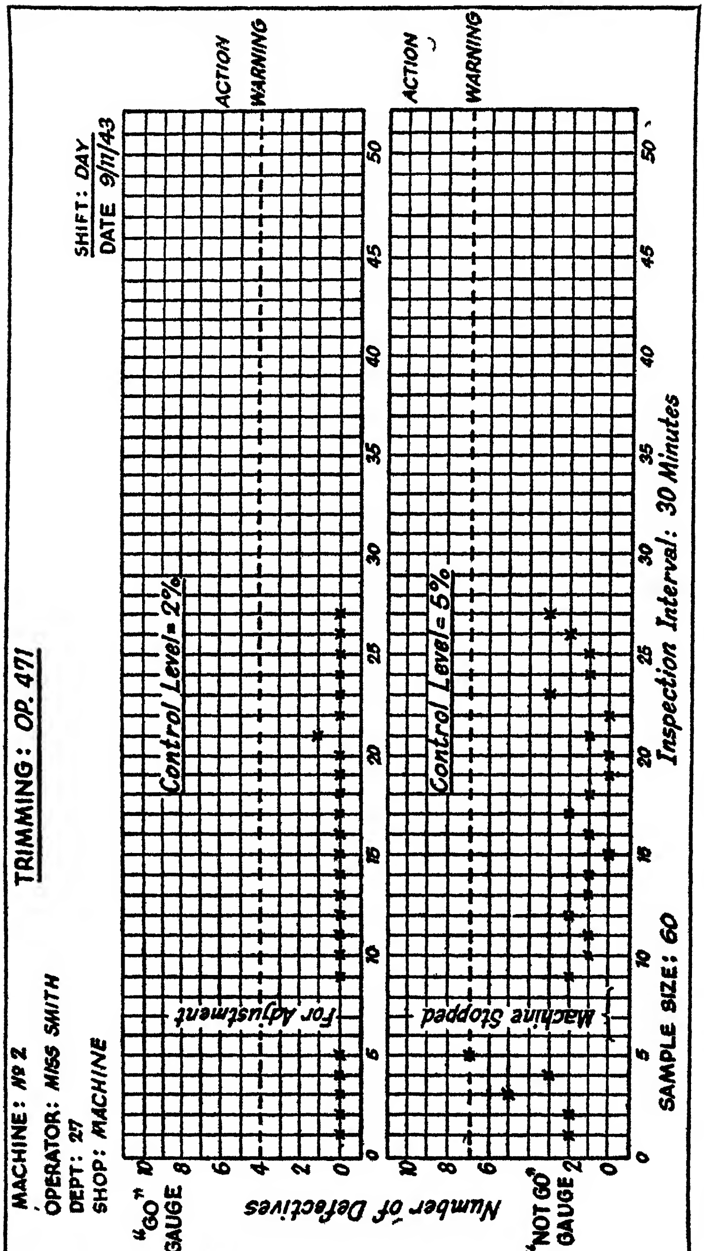


Fig. 25. Two-way Control Chart (Control Levels: 2 per cent. for "Go" Gauge and 5 per cent. for "Not Go" Gauge)

lines respectively. The machine stoppage at the 5th sample may perhaps be questioned. But the occurrence of 7 defectives on the "not go" chart almost immediately after the like occurrence of 5 defectives leads one to suspect a change for the worse in the rate of defective production during the period between the 2nd and 5th samples. This suspicion is confirmed by the effect of the machine adjustment on the subsequent sampling results.

It will be seen from Fig. 25 that the achieved process average was in each case well below the aimed-at control level. In the case of product failing to pass the "go" gauge we have, with only one defective in 24 samples,

$$\bar{p}_1=\frac{100\times 1}{24\times 60}=0{\cdot}07 \text{ per cent.}$$

as against a specified 2 per cent. defective. In the case of product failing to pass the "not go" gauge there were in all 42 defectives in the 24 samples, so that

$$\bar{p}_2=\frac{100\times 42}{24\times 60}=2{\cdot}92 \text{ per cent.}$$

as against a specified 5 per cent. defective. In point of fact, after a few months' running of the two-way chart shown in Fig. 25, the aggregate percentage defective fell from the above figure of $0{\cdot}07+2{\cdot}92=2{\cdot}99$ per cent. to under 1 per cent., when the two-way chart was abandoned in favour of a standard chart for (overall) percentage defective using a much reduced sample size so as to economise in inspection effort.

The Tippett Dual Control Chart. The two-way control chart for defectives, due originally to Dudding and Jennett*, has the important advantage that it shows, more or less at a glance, what kind of change in the production characteristic is giving rise to the increase (or decrease) in the rate of defective production. As we mentioned at the beginning of this chapter, an alteration in the production of defectives may be brought about either by a change in position of the production characteristic or else by a change in its spread relative to the drawing limits. (These two effects, it will be remembered, were illustrated in Fig. 6, and were discussed in some detail in the relevant section of Chapter III.) Now a change in position, such as would be brought about by a dimensional drift due to tool wear, means that less of the production characteristic will be cut off by one drawing limit and more will be cut off by the other. Since the areas so cut off represent the percentages of product falling outside the limits it is clear that a change in position of

* See *B.S.*600*R*-1942 (*Quality Control Charts*), Section 4.F.

the production characteristic will manifest itself as a diminished process average in one-half of the two-way chart simultaneously with an augmented process average in the other half In the same way an increase or decrease in spread of the production characteristic will be revealed by a simultaneous increase or decrease in the process averages in both halves of the chart.

This valuable feature of the two-way control chart has led to its development by Tippett as a substitute for the highly sensitive dimensional control charts which use the sample average $\bar{x}$ as a measure of dimensional drift and the sample range w as a measure of dimensional spread, i.e., process variability. As an introduction to this very important development we cannot do better than quote Dudding and Jennett on the subject. Referring to a two-way control chart based on a sample size $n=100$ and a control level of $\bar{p}=0$ 5 per cent. for each chart (i.e., an overall rate of defective production equal to 1 per cent.), they say* .—

"If there are engineering reasons for expecting the average size of the product to be large or small, due to tool setting, for example, then the distribution of the points between the two charts will quickly show in which direction a correction to the setting should be made.

"Further, if changes in dimension arise mainly from tool wear and not from erratic behaviour of the manufacturing unit, then increase in defectives will be due to a drift in average size rather than an increase in the dimensional spread. In such circumstances it might prove valuable, using two charts, to set the tool initially so that rather more than one defective will be expected on the average to appear on one chart, but none on the other. As tool wear increases, the number of defectives plotted on one chart will tend to reduce, whilst eventually the number plotted on the other will tend to increase. Thus information will be continuously available as to the state of the tool, and production could be stopped when too many defectives, say three, appear on the second chart.

"It is also obvious that if the manufacturing unit is of such a type that erratic behaviour is the more likely fault to develop, then the plotted points are likely to dodge about from the 2 or 3 level on the one chart to the 2 or 3 level on the other. Such events would be a definite indication that tool wear was not a principal factor governing change in dimension, but that some uncontrolled part of the manufacturing unit was giving rise to the change."

The effect of dimensional drift on a two-way control chart is shown in

* *B.S.*600*R*-1942, p. 22.

Fig. 26, which is based on the results of a sampling experiment carried out by the author. The aimed-at control level in each chart is 1 per cent defective which, with the chosen sample size of $n=100$, gives $\bar{c}_1=\bar{c}_2=1$ as the expected number defective per sample for each gauge and $c_1=c_2=4{\cdot}4$ as the corresponding control limit value (see Chart I of Appendix B). The upward drift in average dimension, i.e., in the *dimensional* process average $\bar{X}$, is clearly shown by the gradually increasing number of defectives per sample, c_1, in the "go" chart coupled with the corresponding decreasing number defective, c_2, in the "not go" chart. In other words, whilst the overall rate of defective production remains virtually unchanged at about 2 per cent., the percentage of product exceeding the upper dimensional limit is increasing, and that exceeding the lower dimensional limit is at the same time decreasing.

The extent of this movement of the production characteristic in the direction of increasing dimension may be judged from the following tabulation —

Sample Numbers	"Go" Gauge		"Not Go" Gauge		Both Gauges	
	Aggregate Defectives	Average % Defective	Aggregate Defectives	Average % Defective	Total Defectives	Overall % Defective
1-20	19	0·95	15	0·75	34	1 70
21-40	29	1·45	10	0·50	39	1 95
41-55	32	2 13	1	0·07	33	2 20

The three pairs of process averages, $\bar{p}_1$ and $\bar{p}_2$, for the percentage of product failing to pass each of the gauges are shown by the chain-dotted lines in Fig. 26. It will be observed that the overall process average, $\bar{p}=\bar{p}_1+\bar{p}_2$, is close to the aimed-at value of 2 per cent. defective; but that it tends to increase slightly with the increase in average dimension, in spite of the fact that the sampling experiment was arranged so as to simulate a constant variability in dimension (i.e, a constant precision of the production process as measured by the standard deviation σ of the production characteristic*). A little consideration will show that such an increase is bound to occur as soon as the process average for one-half of the chart—the lower half in the case of Fig. 26—has fallen to zero per cent. defective. However, there are certain theoretical reasons, which need not concern us, why a similar increase may occur before either $\bar{p}_1$ or $\bar{p}_2$ has become zero; it is a question of the relationship between the spread of the production characteristic and that of the drawing limits, i.e., between the natural tolerance of the job and the drawing tolerance specified.

* See page 37.

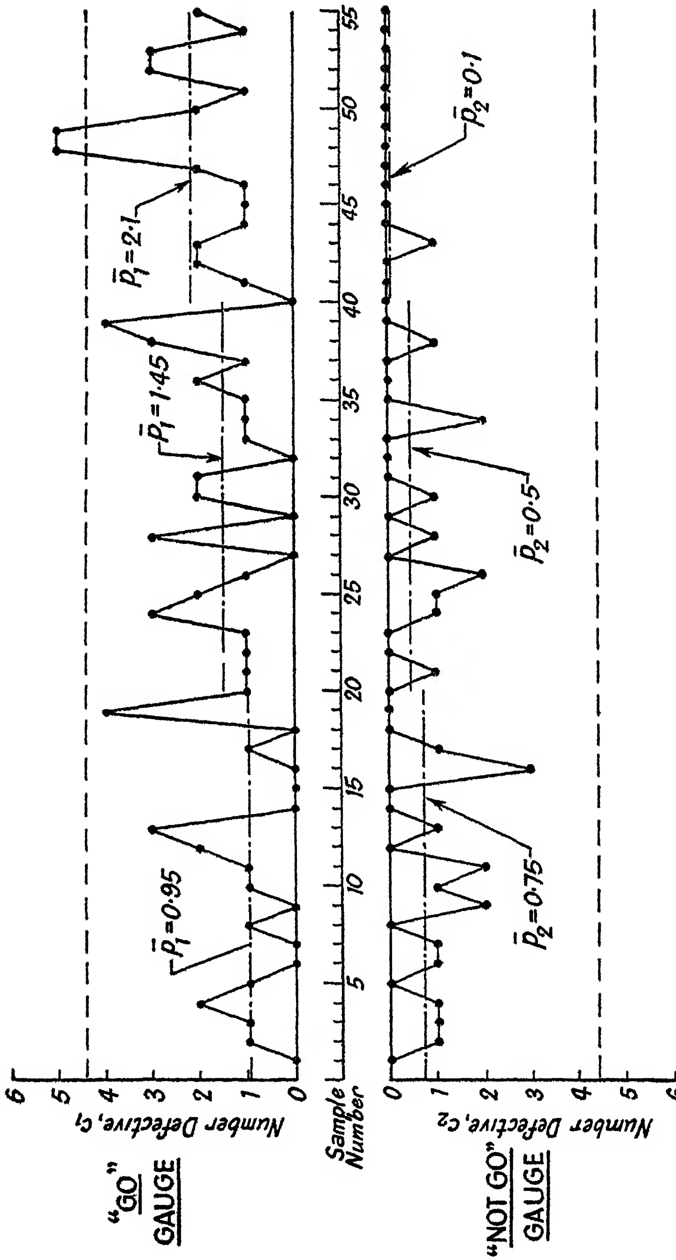


Fig. 26. Two-way Control Chart (Control Level. 1 per cent. Defective for Each Limit)

The possibility of extending the principles of the two-way control chart for defectives so as to achieve a simultaneous control of average and dimensional variability, analogous to that obtained by the use of dimensional control charts for sample average and sample range, has quite recently been realised as the result of an ingenious development by one of our leading industrial statisticians, L. H C. Tippett*. This development consists in utilising the data underlying the usual two-way control chart, that is to say, the sampling results given by " go " and " not go " gauges separately, to construct a dual control chart in which the quantities plotted are (1) the difference between the two numbers defective, and (2) the sum of these numbers. As Tippett has shown, the difference $a=c_1-c_2$ serves as an efficient measure of dimensional *average*, $\bar{X}$, whilst the corresponding sum $v=c_1+c_2$ serves as an equally efficient measure of dimensional *variability*, σ.

The optimum efficiency is obtained when the control levels for the " go " and " not go " gauges are each in the neighbourhood of 10 per cent. defective, but it is not essential that $\bar{p}_1$ and $\bar{p}_2$ should exactly equal 10 or that $\bar{p}_1=\bar{p}_2$. Since this means an overall rate of rejection by both gauges in the region of $\bar{p}=\bar{p}_1+\bar{p}_2=20$ per cent., it is clear that special inspection gauges will be required, set to limits determined from an Inspection Limit Ratio given by—

$$\text{I.L.R.}=1-\frac{3}{4}\,\frac{(\text{Critical R.P.I.})}{(\text{Actual R.P.I.})} \qquad \text{(8)}$$

and calculated in accordance with the methods described in connection with equation (7).

The procedure for constructing the Tippett dual control chart is then somewhat as follows : In the first place, with $\bar{p}_1$ and $\bar{p}_2$ known in advance, calculate the corresponding control levels for " average " and " variability," viz. —

$$\bar{a}=\bar{c}_1-\bar{c}_2=\frac{100}{n}\,(\bar{p}_1-\bar{p}_2) \qquad \text{(9)}$$

and

$$\bar{v}=\bar{c}_1+\bar{c}_2=\frac{100}{n}\,(\bar{p}_1+\bar{p}_2) \qquad \text{(10)}$$

where n is the sample size. Then calculate the control limit values for a from

$$a=\bar{a}\pm3\sqrt{\bar{v}-\bar{a}^2/n} \qquad \text{(11)}$$

and those for v from

$$v=\bar{v}\pm3\sqrt{\bar{v}-\bar{v}^2/n} \qquad \text{(12)}$$

* *Cf.* L. H. C. Tippett : " The Efficient Use of Gauges in Quality Control," *The Engineer*, 23rd June, 1944.

The plus sign corresponds to the upper control limit and the minus sign to the lower control limit. In the case of the lower control limit for v, if $\bar{v}$ is less than about 9 the numerical value given by equation (12) will be negative, in which case the control limit is taken as $v=0$.

As an illustration of the Tippett dual chart, we shall take the example of the two-way chart shown in Fig. 26. Here $\bar{p}_1=\bar{p}_2=1$ and $n=100$, so

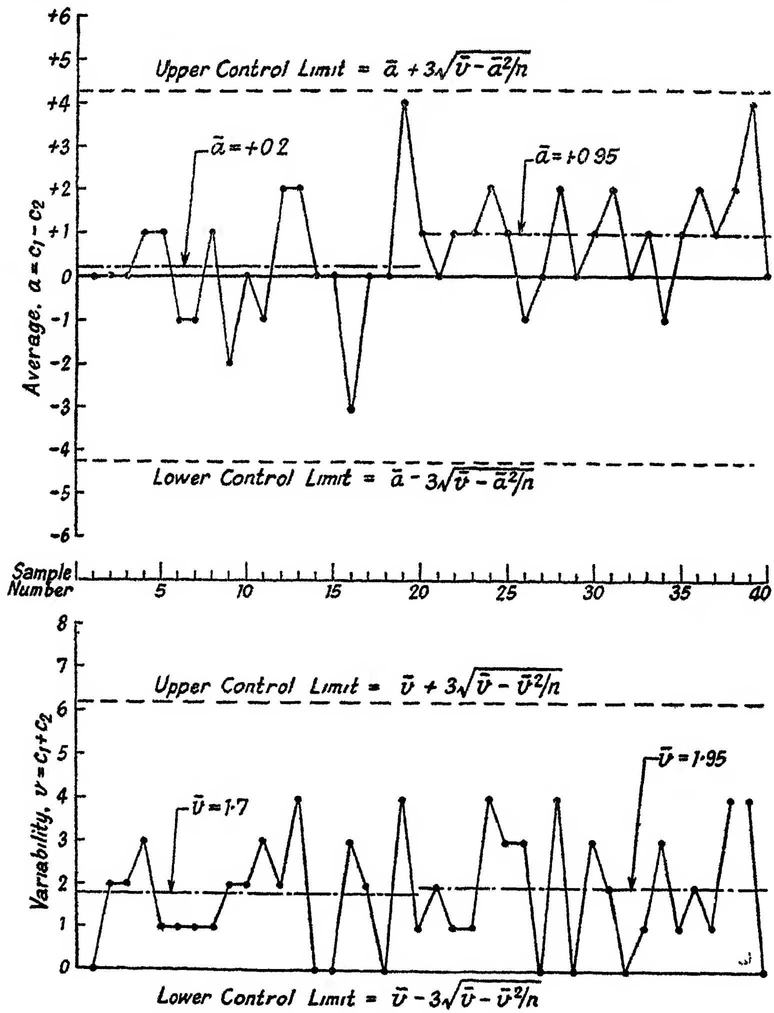


Fig. 27. TIPPETT DUAL CONTROL CHART (CONTROL LEVELS: $\bar{a}=0$ AND $\bar{v}=2$)

that the control levels for a and v are $\bar{a}=0$ and $\bar{v}=2$ respectively. Also the control limits for a are :—

$$a=0\pm3\sqrt{2-0}=\pm3\times1{\cdot}414=\pm4{\cdot}24,$$

whilst those for v are :—

$$v=2\pm3\sqrt{2-0{\cdot}04}=2\pm(3\times1{\cdot}4)=6\ 2 \text{ and } 0,$$

since the lower value comes out negative. The dual control chart is shown in Fig. 27 for the first 40 sampling results. The upward drift in average dimension is very clearly shown by the a-chart, whilst the v-chart as clearly indicates an almost constant level of variability. Neither chart shows any lack of control at the given levels, but it is left as an exercise to the reader to complete the dual chart by plotting the remaining 15 sampling results from the data of Fig. 26. It will be found that the a-chart gives a clear indication of excessive upward drift in average dimension at the 48th and 49th samples. In fact, the achieved "process average" value of a for the last 15 samples will be found to be $\bar{a}=31/15=+2{\cdot}06$, which is far in excess of the aimed-at value $\bar{a}=0$, corresponding to equal values of percentage defectives for the "go" and "not go" gauges. The corresponding process average value of v will in turn be found to be $\bar{v}=33/15=2\ 20$, which is quite compatible with the aimed-at value $\bar{v}=2$, as determined from the given rate of defective production (2 per cent of product outside the drawing limits).

In the second place, if the control levels, $\bar{p}_1$ and $\bar{p}_2$, are not known in advance—as in general they won't be, since they are rarely specified and even then the gauge limits may be inaccurate—the corresponding levels for a and v must first be found from the sampling inspection data, after which the control limits can be calculated and inserted on the chart. This is the usual control chart procedure, exemplified in detail by the data sheets (Tables IV and V) in Chapter IV for quality control based on dimensional measurement. Taking the first 20 samples of Fig. 26 by way of illustration, the sampling inspection results give :—

$$\bar{c}_1=\frac{\text{Total number of rejections by "go" gauge}}{\text{Total number of samples}}=\frac{19}{20}=0{\cdot}95$$

$$\bar{c}_2=\frac{\text{Total number of rejections by "not go" gauge}}{\text{Total number of samples}}=\frac{15}{20}=0\ 75$$

and hence the required control levels become :—

$$\bar{a}=\bar{c}_1-\bar{c}_2=0{\cdot}95-0{\cdot}75=+0{\cdot}2$$
$$\bar{v}=\bar{c}_1+\bar{c}_2=0{\cdot}95+0{\cdot}75=1{\cdot}7$$

the control limits on the a-chart would then be placed at

$$a= +0{\cdot}2 \pm 3\sqrt{1{\cdot}7-(0{\cdot}2)^2/100} = +4{\cdot}11 \text{ and } -3{\cdot}71$$

whilst the control limits on the v-chart would be located at

$$v=1{\cdot}7 \pm 3\sqrt{1{\cdot}7-(1{\cdot}7)^2/100}=5{\cdot}58 \text{ and } 0.$$

The interpretation of movements of a and v is much easier than that of changes in c_1 and c_2 in the two-way control chart. An upward or downward trend in a denotes an increase or decrease in average dimension (as measured by $\bar{X}$ in the dimensional chart for sample average $\bar{x}$), and this *may* be accompanied by an increase in v. But an upward trend in v alone denotes an increase in dimensional variability (as measured by $\bar{w}$ in the dimensional chart for sample range w), that is, a falling off in precision of the production process.

CHAPTER VI

THE ORGANISATION OF A QUALITY CONTROL SYSTEM

WITH one notable exception the available literature on the subject of quality control technique gives practially no information on the organisation of quality control procedures and the establishing of appropriate shop routines for their operation.* This is, of course, understandable when one considers that each manufacturing concern, each factory, and even each machine shop has very largely to work out its own salvation in the establishing and running of a quality control system which best meets the requirements peculiar to its own organisation. It is clearly impossible, even if it were desirable, to lay down hard and fast rules for operating Quality Control which would prove universally acceptable. We must never be allowed to forget that the statistical method of controlling product quality during manufacture is a production aid and not an independent scheme of things imposed from without. Quality Control, to have any measure of success at all, must be grafted on to the existing organisational structure and must progress through the willing and intelligent co-operation of those whom it immediately touches; in the main, inspection and production personnel and, to a more limited extent, planning engineers and designers.

To say that there is no royal road to Quality Control does not mean, however, that guidance cannot be given in the planning of appropriate routines or in the allocation of responsibilities—who should prepare and issue the control charts; who is to fix the control limits, and how; who should take what action when a point on a chart falls outside one or other of the control limits; what is to be done with the suspected bulk product whose sampling yields such evidence of process instability, and how is it to be disposed of without interrupting the normal flow of work. Our aim in the present chapter is to suggest, and to illustrate by actual example, some of the ways in which problems of this kind are conveniently solved. The reader will no doubt find that many of the precepts given in the following sections are in harmony with his own ideas of shop organisation, whilst others likewise may fail to meet with his approval for one reason or another not connected with Quality Control as such.

---

* The exception is provided by the *B.A.C. Quality Control Handbook* first published in 1943 by the Bristol Aeroplane Company for use throughout the machine shops of its Aircraft Division.

Sampling Routine and Process Inspection Records. As we saw ir Chapter III, the basis of all quality control technique is sampling inspec tion carried out in a systematic manner. The " floor " inspector whos job it is to patrol the machines under his control is made to visit eacl machine at regular intervals, to inspect—by measuring and/or gauging plus visual examination—a sample of n individual piece parts being currently produced, and to record the results of his inspection in a perma nent form.

The procedure for recording this information may be either of th following :—

(a) *Runner System.* The patrol inspector records the samplin inspection results on a printed slip provided for this purpose an gives it to a " runner "—a person whose function it is to go roun the machine shop at predetermined times to collect such informa tion from the shop inspectors. The runner takes this slip to th view room or a similar centralised inspection area and passes i over to the clerical section in charge of the preparation and plottin of control charts. The information on the slip is then posted to th inspection data sheet and the appropriate points are plotted on th control charts, which should be kept in a frame mounted in a pro minent position for the foreman inspector to see. (The contro chart frames may be placed side by side in racks convenientl located at eye level.)

(b) *Inspection Bench System.* Each patrol inspector records th sampling inspection results on the data sheet and fills in the contro charts himself at his inspection bench, where the data sheets ar kept in suitable racks. The control charts are normally kept i transparent covered frames mounted adjacent to or above th machines so that the progress of each job can be seen by operator tool-setter and inspector alike.

The runner system is in some ways the better of the two and is mor suited to the larger factory organisations with several machine shops In some cases the runner takes the sample of piece parts to the centra inspection area where they are examined by the inspection staff, who ma either record the results and plot the points on the charts themselves or alternatively, record the results on a printed slip which is then passed o to the clerical group located in the same area. The inspection benc system is usual in the smaller factory and has the advantage that th floor inspector is directly in touch with the results of his own work. Th author is a firm believer in the posting of control charts on or near th

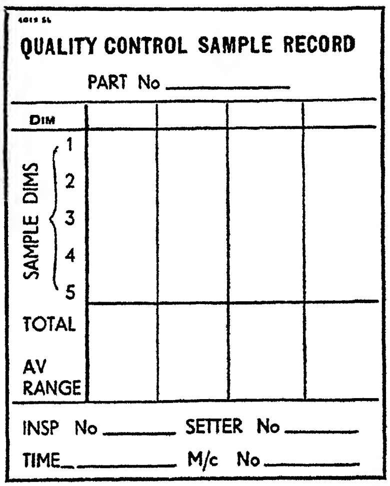
machines. Where this is not done there is little chance of getting the rank and file in the machine shop familiar with Quality Control, and there is danger of inducing the attitude of "out of sight, out of mind" among inspection personnel.

A typical sampling inspection record slip is shown in Fig. 28, based on a sample size $n=5$ and covering up to 4 separate dimensions. The associated inspection data sheet is depicted in Fig. 29 In considering the layout of such a card it is as well to bear in mind that the results of sampling inspection should be recorded in such a way as to facilitate—

(1) the plotting of control charts;

(2) the tracking down of assignable causes (of process instability);

(3) the comparative analysis of successive batch records.


QUALITY CONTROL SAMPLE RECORD

PART No ______

DIM				
SAMPLE DIMS 1				
2				
3				
4				
5				
TOTAL				
AV RANGE				

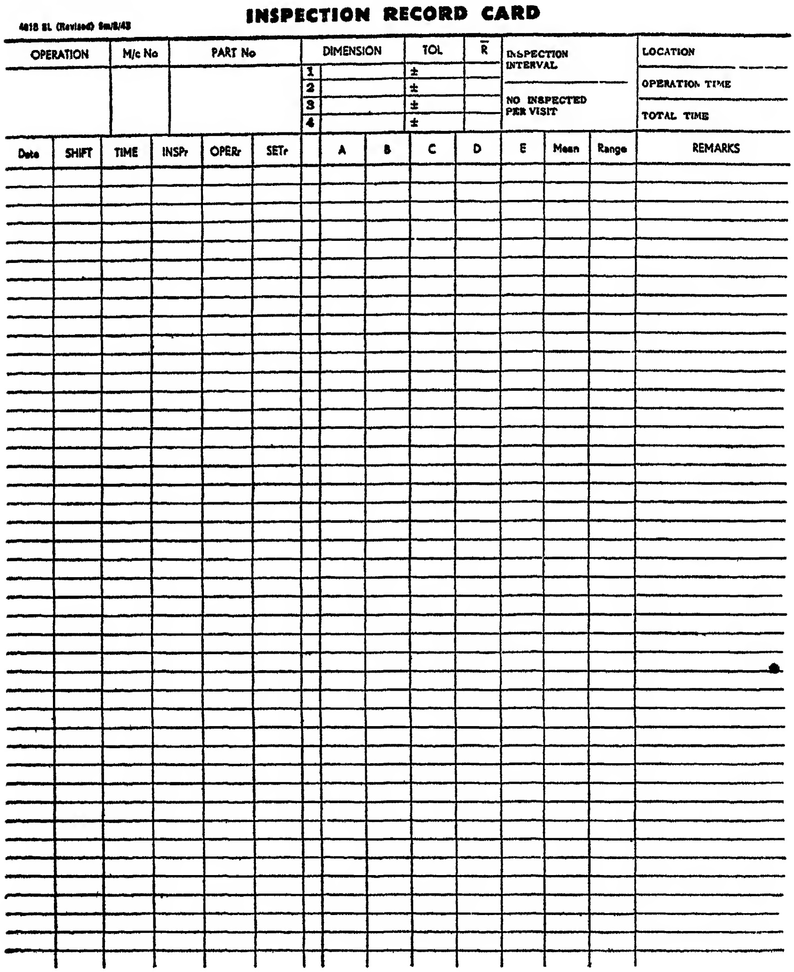
INSP No ______ SETTER No ______

TIME ______ M/c No ______

Fig. 28. Sampling Inspection Record Slip

As we saw in Chapter IV, the third requirement is of considerable importance to production planning on the one hand, and to engineering design on the other hand Item (1) is catered for in Fig. 29 by the provision of the "mean" and "range" columns immediately after the five columns headed "A," "B," "C," "D" and "E" in which are entered the five dimensions constituting the sample measurements. Item (2) is covered by the first six columns, of which the fifth and sixth are in practice the most important. Lack of control is nearly always associated with either poor tool setting or else carelessness or lack of skill on the part of the operator. Item (3) is, in a sense, taken care of by the small column at

the top of the card headed "$\overline{\text{R}}$," signifying the mean range (in samples of 5) achieved in the processing of each of the four (or less) dimensions during that run of the job to which the completed record card relates.*



INSPECTION RECORD CARD

4818 SL (Revised) 5m/8/43

OPERATION	M/c No	PART No	DIMENSION		TOL	$\overline{\text{R}}$	INSPECTION INTERVAL	LOCATION
			1		±			OPERATION TIME
			2		±		NO INSPECTED PER VISIT	
			3		±			TOTAL TIME
			4		±			

Date	SHIFT	TIME	INSPr	OPERr	SETr		A	B	C	D	E	Mean	Range	REMARKS

Fig. 29. Inspection Record Card

* Early work on Quality Control in this country was greatly influenced by *B.S.*1008-1942 (*Quality Control*) in which *R* is the symbol used to denote sample range. Unfortunately in statistical work this letter has long been established as symbolising another quantity altogether, and hence the letter *w* has now become the accepted symbol for range.

The method of recording the four sets of sample dimensions on process inspection data sheets of this type will be dealt with in the next section.

The comparative analysis of successive process inspection records for the same job—item (3) cited above—is almost as important as is the use of the control chart in preventing or minimising defective production, batch by batch. Such an analysis is in the nature of a supervisory task with the object of ascertaining whether a machine is consistently able to produce a given dimension within the drawing limits specified. In this respect the R.P I. theory developed at the end of Chapter III, and illustrated by a few examples in Chapter IV, is a useful weapon in the armoury

S S & S (M A) LTD.
RP 1815

QUALITY CONTROL RECORD

DESCRIPTION CODE

Sect	Op No	M/C No	Setter	Operator	Shift	Rate Per Hour	Shop Order	Qty	Inspector	Sample Size	Inspection Interval	Date

Fig. 30 (a). Quality Control Record (*Front*)

of the inspection superintendent when standing up for his department—as, alas, he is often called to do—against the several or joint onslaughts of the shop superintendent and the chief planning engineer. As a matter of fact it is by now generally accepted, as one of the secondary benefits to be gained from Quality Control, that it provides for the first time a wholly objective instead of a largely opinionative basis of argument in such cases of dispute.

To facilitate such comparative analyses a quality control record card of the type illustrated in Fig. 30 is likely to prove useful. Each line on the front of the card, shown in Fig. 30 (*a*), gives a summary of the main items

on the sampling inspection record (e g., Fig. 29) relating to one run of a particular job. On the back of the card, shown in Fig. 30 (*b*), are entered the corresponding numerical data obtained from the quality control record proper, viz :—

Number =Total number of *samples* inspected
Ave. X =The achieved process average, $\bar{X}$.
Low Control =Lower control limit for $\bar{x}$
High Control=Upper control limit for $\bar{x}$
Ave. Range =The mean sample range, $\bar{w}$.
Low Control =Lower control limit for w
High Control=Upper control limit for w
Dimension =The nominal dimension, D
$D+T$ =Upper drawing limit.
$D-T$ =Lower drawing limit.
Level =The off-set, $D-\bar{X}$ (either + or −).
Ratio =The control ratio.*

Inspector's Remarks

Special Notes

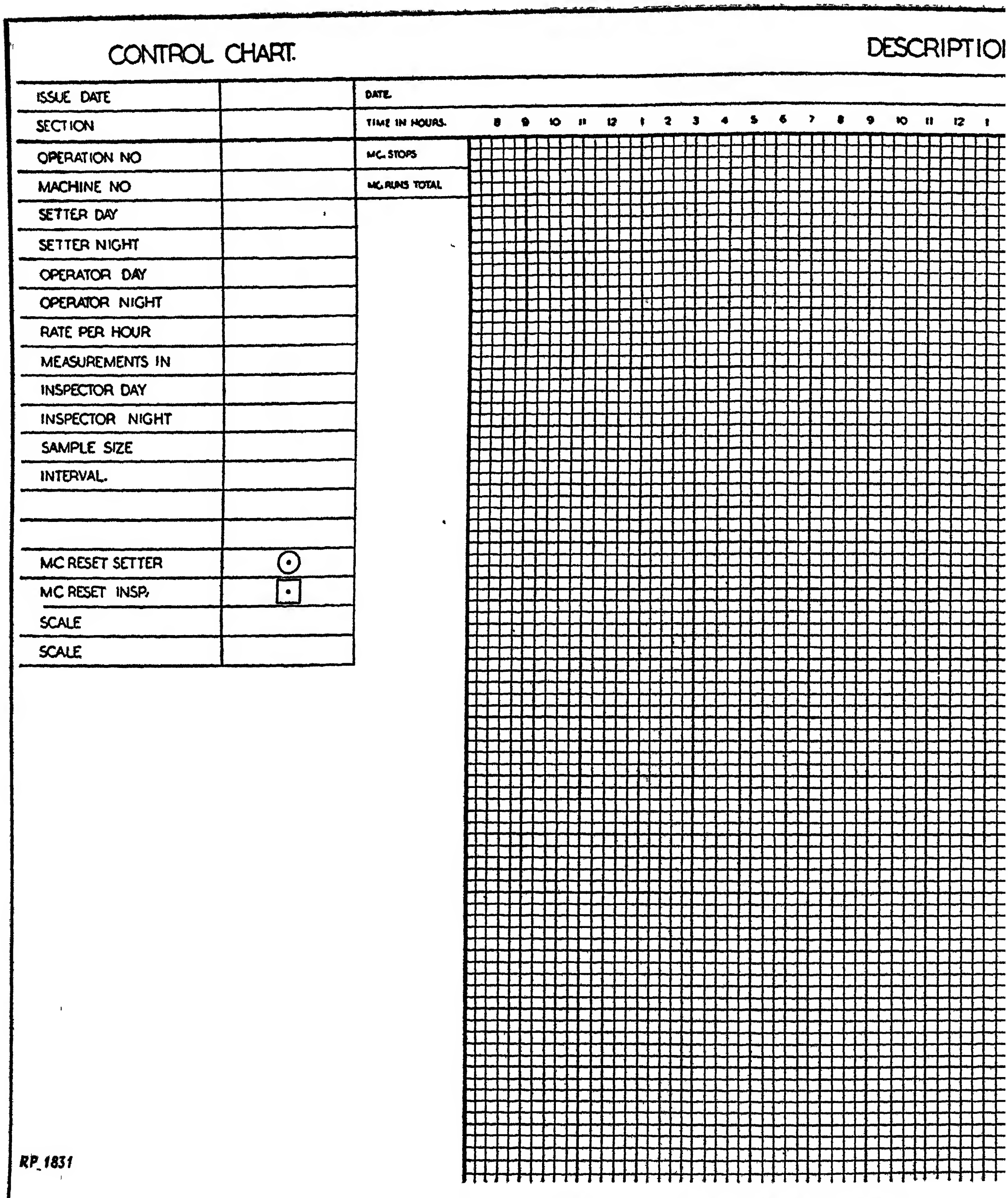
QUALITY CONTROL RECORD

Number						
Ave X						
Low Control						
High						
Ave Range						
Low Control						
High						
Dimension						
D + T						
D − T						
Level						
Ratio						

Fig. 30 (b). QUALITY CONTROL RECORD (*Back*)

Fig. 38 shows another form of record card covering (*a*) dimensions subject to quality control and (*b*) dimensions subject to check inspection

* As explained in Chapter III, the relative precision index is a more useful measure of machine capability (to meet drawing limits) than the control ratio.



CONTROL CHART.

DESCRIPTIOI

ISSUE DATE	
SECTION	
OPERATION NO	
MACHINE NO	
SETTER DAY	
SETTER NIGHT	
OPERATOR DAY	
OPERATOR NIGHT	
RATE PER HOUR	
MEASUREMENTS IN	
INSPECTOR DAY	
INSPECTOR NIGHT	
SAMPLE SIZE	
INTERVAL.	
MC RESET SETTER	⊙
MC RESET INSP.	⊡
SCALE	
SCALE	

DATE

TIME IN HOURS. 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1

MC. STOPS

MC. RUNS TOTAL

RP 1831

Fig. 31. Pre-printed Co

CODE NO·

1 2 3 4 4 6 7 8 9 10 11 12 1 2 3 4 5 6 7

only. Card No. 1 covers operations 1 and 2 (on the front) and operations 3 and 4 (on the back), card No. 2 in the same way covers operations 5, 6, 7 and 8; and so on. A record card of this type constitutes, in effect, an *inspection layout* for the process operations concerned. It gives in a permanent form all the inspection information relevant to the correct processing of a particular job

Now for a word or two as regards control charts and their maintenance. Some firms prefer to use specially printed charts, of which typical examples are given in Figs. 31 and 39 Others in turn favour commercial squared (graph) paper overprinted with certain items, such as the times of sampling inspection; job, machine and operation number (Fig. 15 and 16); and even drawing limits and blank dimensional scales (Fig. 34). Cheap graph paper is all that is required for control chart purposes, the ruling preferred by the author being ½-inch squares subdivided by ⅕ths (i e., 10 lines per inch). The most convenient dimensional scales to choose have already been indicated on p. 52. No standard convention as yet applies to the method of distinguishing between drawing limits, control limits and, if required, nominal or process average values. Probably the most widely accepted convention is solid lines for the drawing limits ($D \pm T$) and the drawing tolerance ($2T$) on the average and range charts respectively; dotted lines for all control limits; and chain-dotted lines for the process average $\bar{X}$ and mean range $\bar{w}$. Alternatively, one may with advantage use different coloured lines, preferably black for drawing limits, process average, etc, and red for control limits. Some like to show drawing limits in red and control limits in green. Others prefer to keep to black lines throughout, and to use red and green pencilled dots to distinguish between the plotted points for day and night shifts.

Finally, where the clerical work itself is concerned, stress should be laid on the importance of legibility as well as accuracy in the recording of sampling inspection data, the filling in of quality control record cards (e.g., control-chart summaries of the type illustrated by the example of Fig. 30), and the preparation and plotting of control charts A further point which requires constant watching is the question of alterations. Nothing is more disconcerting when examining a data sheet than to find an altered dimension with no explanatory note or initial to substantiate it, or an altered drawing number or operation number. In such circumstances, there is no alternative but to investigate the matter to make sure that the altered figure is the correct one—which takes time which could be better spent, and naturally is an irritant to the persons having to settle the query which arises.

It is for this reason that the rule is often enforced that all alterations must be made by a supervisor in red and initialled, and this rule must then be strictly adhered to for the benefit of all concerned.

Those dealing with the clerical side of the system have equal and important responsibility for its success with any of the personnel directly or indirectly concerned Not least because not only do the shop inspectors depend on the accuracy of the original data sheets and charts, but those dealing with the completed sheets, etc., for progress purposes will often notice small points of inconsistency and obvious errors which should be dealt with.

In this connection, the following notes will indicate what is in mind :

1. The following should always be brought to the notice of a supervisor—
   (*a*) " Unofficial " alterations.
   (*b*) Obvious errors.
   (*c*) Inconsistency of data.
   (*d*) Any part of the system not working smoothly—most of these things can be put right *if they are known*.
2. See that a new data sheet, etc., is initialled by a supervisor before being put into operation.
3. All amendments must be made by crossing out the incorrect data and re-writing the information. Actual alteration of figures, etc., is misleading and often illegible
4. The record cards must be kept in strict drawing order. Much time will be lost and duplication of records result if the cards are allowed to get out of order at all, for when a new operation is advised, a new card will be made out unnecessarily if there is already a card in the box but out of order.
5. The following instructions apply to the use of the record card :
   (*a*) Cards will be prepared in advance and kept on file ready for immediate issue
   (*b*) Average dimensions and control limits calculated after the first controlling of an operation will be inserted, after the chart and data sheet are analysed, by persons detailed for that purpose These persons will also be responsible for carrying on to the card, alterations made by supervisors to data sheets.
   (*c*) The issue number on all cards will be altered as necessary when the drawing is checked against card, etc., by a supervisor before a new batch is commenced.

6. See that the record cards are clear and direct in the information they contain. It should be possible for data sheet and chart to be drawn up from the relevant record card without any hesitation or further investigation.
7. Cultivate system and tidiness and develop a clear-cut way of dealing with the work. This does not apply, of course, only to clerical work, but it does have particular importance in that connection, for unless a regular routine is adopted and kept to rigidly the "paper-work"—which is a vital part of the system—will not be ready when wanted, thereby causing delay and a general annoyance and waste of time.
8. Do everything possible to keep charts and data sheets clean and tidy and help the shop inspectors to do the same. The system of using charts and data sheets for successive batches has been devised not only to save time and give a clearer picture of the operation of manufacture but to save paper. A dirty, dog-eared chart or data sheet cannot be used again. Where paper folders, holders and racks are provided—see that they are used. The little extra time taken in using them will be more than saved somewhere else in the shop.
9. Charts will be filed away after use in two groups:

   (*a*) Those which are unsuitable for use again and

   (*b*) Those which can be used again.

   Both groups should be kept in drawing number order. Charts and data sheets will always, of course, be used to cover successive batches where no break occurs.

   When a new operation is advised, the file containing the charts which are available for use again should be examined to see if there is a chart available to save preparing a new one. If so, the previous order will be separated off by a vertical line as for repeat batches.
10. When data sheets are collected after completion, the section stating whether the control chart is also complete, or being used for a repeat batch, must be completed by the person collecting the sheets. This is necessary to show the whereabouts of the chart to those responsible for analysing data in order to see whether any further inspection is required.
11. Charts when collected should always be kept with the relevant data sheet.

Quality Control Procedure. The establishing of quality control procedure as a standard routine, officially approved by the works management, becomes a necessity so soon as the introduction of control charts

has passed beyond the experimental stage. During that stage the methods described in Chapter IV, especially in connection with the data sheets of Tables IV and V, are no doubt adequate for the purpose of getting a quality control system under way in the machine shop and are likewise appropriate to its operation by technical personnel—drawn from the existing inspection force or, perhaps, from the production planning staff, or else, possibly, from amongst the post-graduate students to be found in the design and research departments of the progressive engineering concern

Such methods, however, have to be broadened down, simplified, regularised and converted into routine instructions before the ordinary machine-shop organisation can be expected to accept Quality Control as part and parcel of its established working procedure. *It is here that, in the author's opinion, a quality control system is most likely to fail when introduced on any scale beyond that of experiment and investigation* Having decided upon the most suitable machinery for inspecting samples, preparing and issuing data sheets and control charts, maintaining process inspection and quality control records, and analysing, recording and filing the results, the next step is to establish appropriate routines covering

(*a*) " First off " inspection ;
(*b*) Patrol inspection ;
(*c*) Quality control supervision ; and
(*d*) Co-operation on the part of production personnel.

In what follows we present some general rules which experience has shown to meet the requirements of efficient operation of a quality control system. A typical set of instructions covering quality control in a medium-sized machine shop is given in Appendix D.

(*a*) " *First-off*" *Inspection.** The action to be taken by a " first-off " inspector with regard to a process operation subject to Quality Control will depend upon whether that operation has previously been so controlled or not. This fact should therefore be indicated on the relevant data sheet (process inspection record card) which, in the majority of quality control procedures, will be issued to the inspector before the commencement of the operation.

OPERATIONS NOT PREVIOUSLY CONTROLLED. In these cases the original setting, as estimated from the average $\bar{x}$ of a standard sample of n piece parts, should be as near to the nominal value D as is practicable. In any event the " first off " sample average should not deviate from D by more than $T/\sqrt{n}$ (i.e., half the drawing tolerance times the critical value of the

* See also Appendix D, Section 2.

control ratio) To allow for normal tool wear, any deviation should be toward the lower drawing limit in the case of outside dimensions, and toward the upper limit in the case of inside dimensions.

OPERATIONS PREVIOUSLY CONTROLLED. In these cases the relevant data sheet should indicate—preferably in *red*—the pre-set control limits calculated from one or more previous runs of the same job (See, for example, Fig 37.) The original setting, as estimated from $\bar{x}$ for the first-off sample, *must lie within these control limits*, tending toward the upper or lower limit according as to whether the dimension is an inside or an outside one

As soon as the setting is correct, and the first-off sample has been passed accordingly by the inspector, the n sample dimensions, as well as the sample average $\bar{x}$ and range w, should be entered on the data sheet (or on the

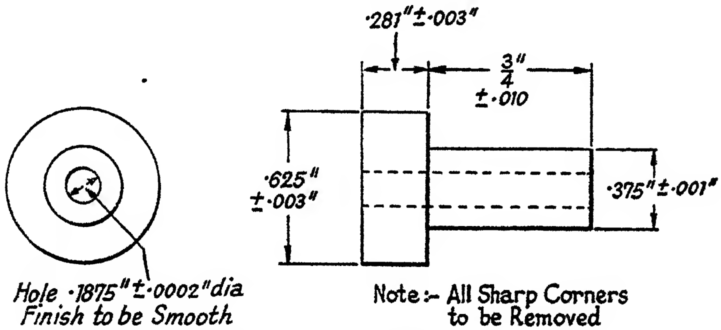


FIG. 32. SHOULDERED BUSH

sampling inspection record slip—see Fig. 28) for each dimension subject to Quality Control. The checking of dimensions not subject to control should at the same time be indicated by means of a tick in the appropriate column of the data sheet, as shown in the examples of Figs. 33 and 37. Finally, the several values of $\bar{x}$ and w should be plotted on the associated control charts.

The first-off inspector will thereupon hand over the data sheet and charts, together with the relevant drawing, to the patrol inspector who will then take charge of the operation. Should a re-setting of the machine become necessary during the run of the job, however, the responsibility for inspection will revert to the first-off inspector until such time as the subsequent first-off sample has been passed by him.

A good rule to follow, too, where circumstances permit, is for the first-off inspector to check all "controlled" machines on his section at the

commencement of each shift, in order to uncover any variations arising from differences between operators Such work should not, of course, be allowed to interfere with his normal duties ; but an effort should be made to check the work of each machine, commencing with the machine to be reached last by the patrol inspector, during the first hour or so of each shift.

Finally, all first-off inspectors should be instructed to draw the patrol inspector's attention to any dimensions, finish, etc., which, from experience,

CR 523 PROCESS INSPECTION RECORD

SCHEDULE NO	PART NO	OPN NO.	SECTION	BATCH SIZE	OPERATION TIME	SERIAL NO
M 1069	PB 4197	1	CAPSTANS	1500	1·65 MINS. PER PART; TOTAL TIME 33 HOURS	1586; INSPECTION INTERVAL 60 MINS

	DIMENSION	TOL
1	0·375" DIA	± 0·001"
2	0·625" DIA	± 0·003"
3	HOLE 0·1875" DIA	+ 0·0002"
4		+

NO INSPECTED PER VISIT: 4 FOR DIAS, 10 FOR HOLE SIZE

(TEA BREAK 5·30 TO 6·00 PM)

DINNER BREAK 11·00 PM TO 12·00 A.M.

DATE	SHIFT	TIME	INSPR	OPERR	SETR	M/C	Prec Insp No 1	2	3	4		A	B	C	D	MEAN	RANGE	SCRAP	Reprocess	RECTIFY	PASSED PER SHIFT
15/6/43	DAY	2·30 PM	589	1126	348	47	✓	✓	✓	✓	1	0·3750	0·3745	0·3745	0·3745	0·3746	0·0005				
											2	0·6235	0·6240	0·6240	0·6240	0·6239	0·0005				
											3	0									
"	"	3·35	719	"	"	"	✓	✓	✓	✓	1	0·3753	0·3748	0·3750	0·3754	0·3751	0·0006				
											2	0·6242	0·6240	0·6246	0·6243	0·6243	0·0006				
											3	0									
"	"	4·50	"	"	"	"	✓	✓	✓	✗	1	0·3754	0·3752	0·3752	0·3753	0·3753	0·0002				
											2	0·6238	0·6240	0·6236	0·6235	0·6237	0·0005				
											3	2 (See Note on Back)							16		
"	"	6·20					✓	✓	✓	✓	1	0·3750	0·3754	0·3774	0·3756	0·3759	0·0024	5			
											2	0·6243	0·6250	0·6248	0·6246	0·6247	0·0007				
											3	0									
"	"	7·15	"	"	"	"	✓	✓	✓	✓	1	0·3752	0·3750	0·3754	0·3750	0·3752	0·0004				
											2	0·6245	0·6245	0·6248	0·6245	0·6246	0·0003				
											3	0									160
15/6/43	NIGHT	8·30	417	1237	219	"	✓	✓	✓	✗	1	0·3756	0·3754	0·3752	0·3756	0·3755	0·0004				
											2	0·6248	0·6248	0·6254	0·6255	0·6251	0·0007				
											3	1						4	10		
"	"	9·40	"	"	"	"	✓	✓	✓	✓	1	0·3756	0·3755	0·3756	0·3757	0·3756	0·0002				
											2	0·6254	0·6258	0·6255	0·6254	0·6255	0·0004				
											3	0									
"	"	10·45	"	"	"	"	✓	✓	✓	✓	1	0·3757	0·3758	0·3756	0·3758	0·3757	0·0002				
											2	0·6255	0·6258	0·6260	0·6258	0·6258	0·0005				
											3	0									
16/6/43	NIGHT	12·15 AM	"	"	"	"	✓	✓	✓	✓	1	0·3748	0·3748	0·3750	0·3748	0·3749	0·0002				
											2	0·6258	0·6258	0·6260	0·6260	0·6259	0·0002				
											3	0									

(CONTINUATION CARDS ISSUED AS JOB PROCEEDS)

Fig. 33 (a). Process Inspection Record (*Front*)

they know to be important as regards subsequent machining operations, and generally to advise the machine-shop inspection force on points of difficulty.

(*b*) *Patrol Inspection.** Before examining the duties and responsibilities of the patrol inspector let us pause for a moment to consider a typical example of the kind of task he has to perform when functioning under a system of Quality Control. As an illustration we shall take the

* See also Appendix D, Section 3.

first capstan turning operation on a shouldered bush, for which the drawing is as shown in Fig. 32. In this particular operation the 0·375 in. and 0·625 in. diameters are turned and the 0 1875 in. diameter hole is drilled and reamed. The component is then parted off from the bar, with an allowance of +0·015 in on the 0 281 in. thickness of head for final finishing to size by a second operation.

This particular part has been selected as a typical case ideally suited to Quality Control. The 0·375 in. diameter portion and the size of hole are

INSPECTOR'S REMARKS

15/6/43 2 30 P.M. First off approved

15/6/43 4.50 P.M. Sharp edges not being removed satisfactorily. Holes running tight. New reamer fitted. 16 parts re-reamed

15/6/43 6.20 P.M. 5 parts scrapped on 0 375" dia. Bad operating. Set-up O.K.

15/6/43 7 15 P.M. Slightly scored finish in hole. Reamer touched up

15/6/43 8 30 P.M. Operator not removing sharp edges satisfactorily. Holes running tight and scoring. Reamer changed 4 parts scrapped 10 parts re-reamed

15/6/43 10 45 P.M. Job stopped. Tending to run oversize on 0 375 dia. Machine re-set. Producing parts at 0 3747" dia. after re-setting. Production recommenced 11.00 P.M.

SPECIAL NOTES

① 3/4" length to be within ±0 010" of nominal

② 0·375" dia portion to be concentric with hole within 0 004", i e 0 008" on clock indicator

③ Finish of hole to be smooth and free from scores

④ Sharp edges to be removed

Note – +0 015" to be allowed on 0 281" thickness of head at parting off

QUALITY CONTROL RECORD

Dimension	1	2	3	4
$\bar{\bar{x}}$				
$\bar{R}$				
N				
3σ				
$\bar{\bar{x}} + 3\sigma$				
$\bar{\bar{x}} - 3\sigma$				
D + T				
D − T				
Level				
Variability				

(Details filled in on last continuation card)

Fig. 33 (b). PROCESS INSPECTION RECORD (*Back*)

both required to be maintained within close limits of accuracy. Dilution of labour in machine shops to-day, affecting tool setting as well as machine operating, means that less skill is available on work of this character, with the result that, without the steadying influence of Quality Control, considerably more defective work would arise than occurred formerly when such operations were performed by more skilled hands.

Referring to the data sheet or process inspection record card (Fig. 33), it will be seen that the 0·375 in. and 0·625 in. diameters have been selected

for control, and also the hole size. The $\frac{3}{4}$ in length from end to shoulder, being relatively unimportant, is subject to a gauge check only and is accordingly included as a "precautionary inspection" item. It accordingly appears on the back of the card under "special notes," together with checks for concentricity, smoothness of hole finish, and removal of sharp edges. The checking of these items is recorded by entering a tick or a cross in one of the columns numbered 1 to 4 in the middle of the record card, the former indicating "O.K." and the latter indicating the occurrence of some trouble whose nature is reported on the back of the card under "inspector's remarks."

With a production rate of approximately 40 per hour and a standard sample size of $n=4$, an inspection interval of 60 minutes is fixed as giving 10 per cent. sampling inspection for the two dimensions subject to quality control by measurement. The hole size is controlled by means of a "go" and "not go" plug gauge, using the method of defectives with a standard sample size of $n=10$ which, in this case, provides for 25 per cent. sampling inspection.

The control limits pre-set on the control chart (Fig. 34) for the 0·375 in. and 0·625 in. diameters were arrived at from analysis of previous batches on the same operation. The spacing of these control limit lines in relation to the engineering limits indicates that past production was sufficiently satisfactory, and a reasonable interpretation to put on the matter is that the operation is controllable judging from previous experience. This is an important psychological point so far as production personnel is concerned, as it does encourage them to produce a job at least as satisfactory as was produced previously, and may perhaps stimulate them to attempt to do even better.

A study of the control chart for the 0·375 in. diameter, shows that at the fourth inspection visit the plotted point for the average dimension for the 4 parts measured fell outside the control limit. No action regarding the machine set-up was taken, however, as investigation showed that only 5 parts out of the 40 produced in the preceding hourly interval were actually outside the engineering limits, and that this was due to bad operating. At the eighth inspection visit, however, the plotted point again fell outside the control limit, and it was noted from the 4 parts measured, and also from the picture presented by the chart, that there was a tendency for the 0·375 in. diameter to run oversize, although no actual oversize parts had been produced except for the 5 previously scrapped due to bad operating. In this case proper action was taken on the evidence presented by the control chart, and the machine set-up was overhauled in time to

prevent the production of defective parts Investigation showed that the tool was beginning to wear, although still giving a good finish, and that if attention had not been drawn to its condition by the control chart more grinding of the tool than would have been desirable would have resulted had the job been allowed to run without overhaul. With regard to the 0·625 in diameter the control chart (Fig. 34) indicates a gradual increase in size, due also to tool wear no doubt. But as the job was still well within control no action was considered necessary as far as the job had run.

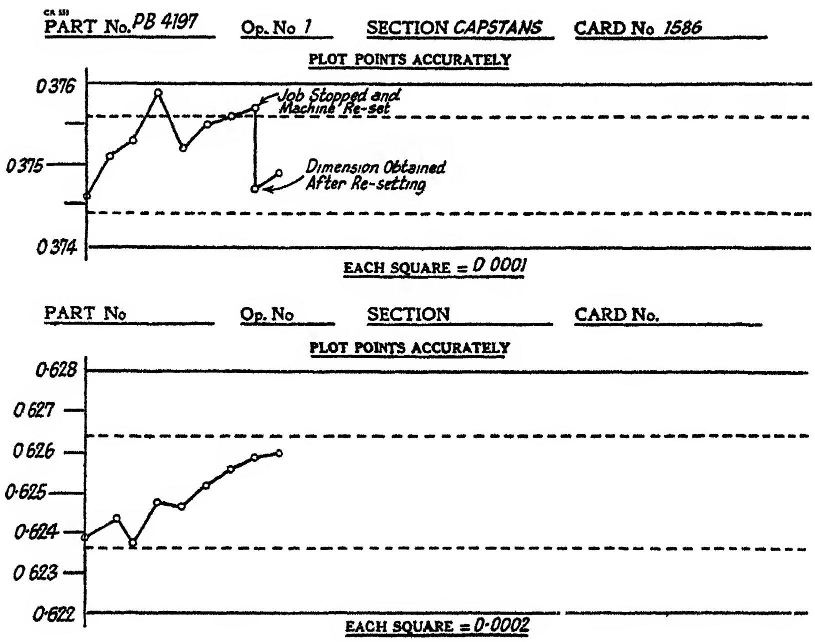


Fig. 34. Dimensional Control Charts

The other control chart (Fig. 35) shows that, with regard to the hole size, trouble occurred on two occasions due to the holes running undersize and being scored. The reamer was changed on each occasion as being the only corrective action possible. The control chart demonstrates that the parts were just over 3 per cent. defective (as estimated from percentage inspection) at the completion of the batch. Four parts had to be scrapped due to bad scoring, and the data sheet shows that out of some 320 parts produced 26 were re-reamed to bring the hole size within limits.

When considering this type of percentage defective control chart, it should be borne in mind that its purpose is *to reveal trends* and present a *general picture of product quality* as disclosed by percentage inspection.* In the case of this particular example, it is true that, while the control chart only shows an overall 4 per cent. defective production on the hole size, it was found necessary to re-ream 8 per cent. of parts produced. The purpose of the control chart was fulfilled, however, *because it drew attention to an unsatisfactory state of affairs on two separate occasions*, and thus led to the necessary corrective action being taken

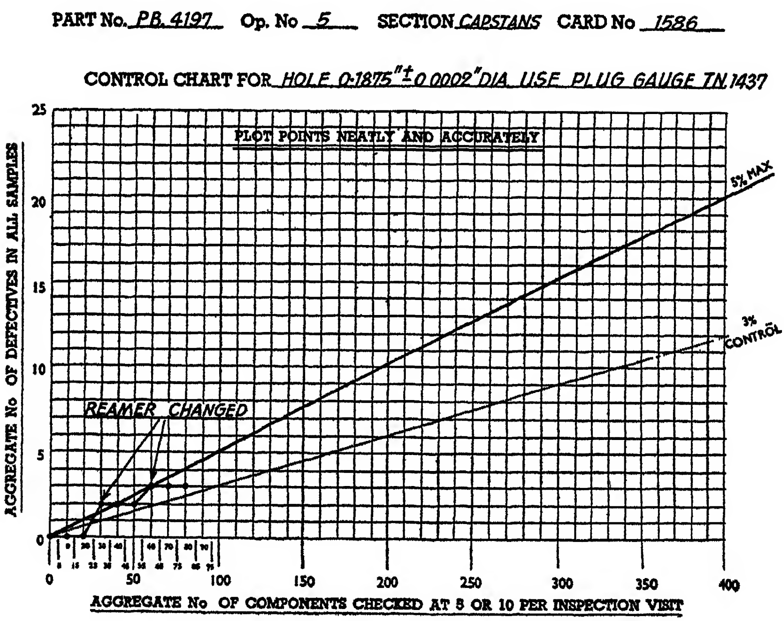


Fig. 35. Defectives Control Chart

To turn now to the duties and responsibilities of the patrol inspector who has to deal with data sheets and control charts such as described above, and who has to interpret their meaning to other interested parties (e.g., tool-setters and operators, shop foremen and planning engineers), we shall consider a further example drawn from a rather more elaborate quality control organisation whose essentials are outlined in Fig. 36. The outstanding features of the prevailing machine-shop organisation are (*a*)

* On this point see Chapter V. Examples illustrating the use of standard charts for percentage defective are given in a later section of the present chapter.

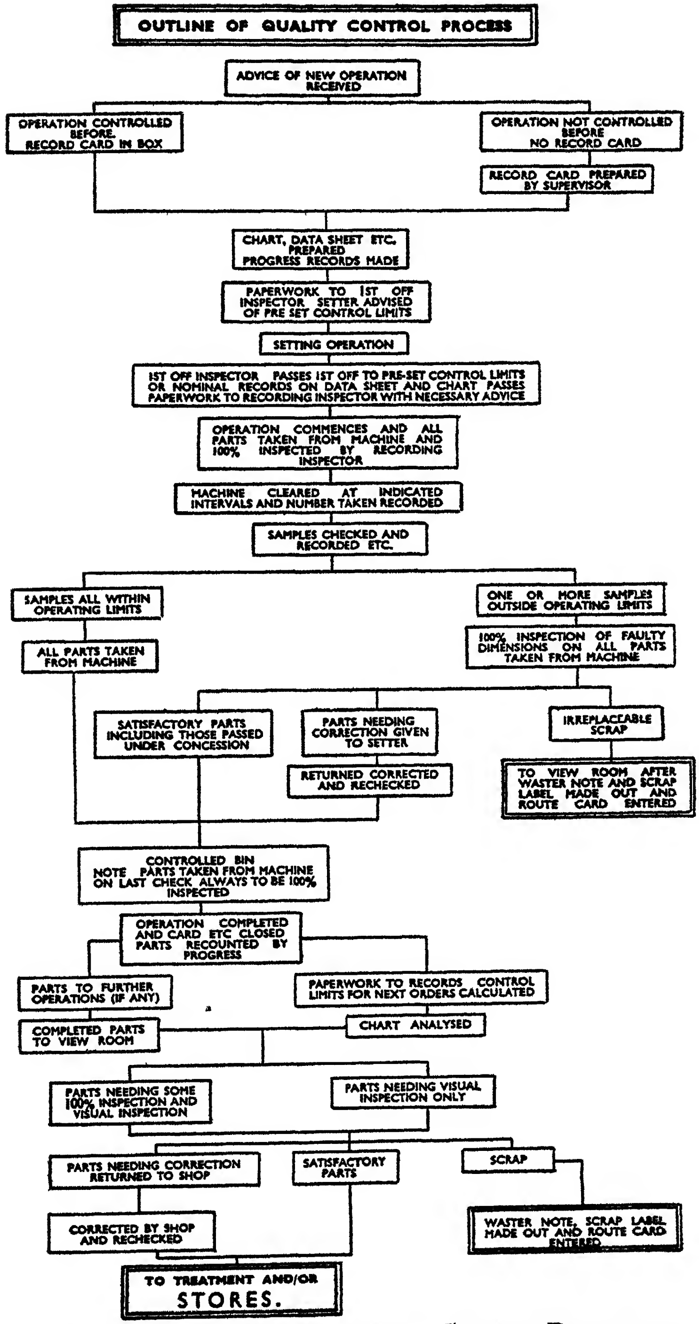


Fig. 36. Flow Chart of Quality Control Procedure

repetitive short orders ; (*b*) removal of all product from a machine at patrol inspection ; and (*c*) detail (100 per cent.) inspection in the " view room " of all product known or suspected to contain defectives. These particular features were determining factors in the establishing of a comprehensive system of Quality Control, and must be borne in mind when considering what follows.

Fig 37 shows the data sheet for the second operation on a special pin, covering three dimensions subject to Quality Control and four further dimensions subject to check inspection only. A code letter is assigned to each of the latter, as shown by the relevant quality control record card (Fig. 38), and the checking of the sample is indicated by a tick in the appropriate column on the data sheet. Dimensional control is established with a standard sample size of $n=4$, and the sample dimensions are generally recorded to the nearest " thou." In the case of drawing limits closer than $\pm 0{\cdot}002$ in., however, these recordings are made to the nearest fourth place of decimals.* An interesting practical detail of this data sheet is the provision of a sub-column for the fourth place of decimals in the case of the sample average and range recordings. *Pre-set* control limits and average values† are shown *in red* in the spaces provided at the foot of the sampling inspection record ; whilst achieved averages and control limits calculated *after* a completed operation are added *in black,* below the actual recordings concerned. A point insisted upon—to which we have already referred—is that no alterations may be made to recorded data except by supervisory staff, any such alterations being entered in *red* and initialled.

As usual the data sheet shows the required number of individual items constituting the sample, i.e., the sample size n, and the sampling inspection interval which in this particular organisation is chosen so that at least 15 per cent. but normally not more than 30 per cent. of the product will be inspected. It is of course important that, as far as possible, these inspection intervals are not exceeded. The sample individuals are taken consecutively as the parts come off the machine so that the sample will give an accurate record of the setting and performance of the machine at the time. This is a standard procedure in Quality Control and the reasons for it have already been discussed in Chapter IV.

The data sheet also shows which dimensions are to be recorded and which need only checking on each sample—the checking of the latter is

* To ensure accuracy, clock gauges or micrometers reading in $0{\cdot}0001$ in. should be used wherever possible on limits of $\pm 0{\cdot}001$ in. or closer.

† The process average is denoted by the symbol $\bar{\bar{x}}$ and the mean range by $\overline{w}$.

									212									

Average Dimension ($\bar{x}$) = ·185   Average Range ($\bar{w}_t$) = · —

± Control = ·002   Upper Control limit = ·187   Lower Control limit = ·183

PRE-SET

ACTION TAKEN AS TO DEFECTIVES ON ABOVE DIMENSION

Sample Group Nos	No off	No to be accepted	'B' No authorising acceptance	No to be corrected	Given to setter time & date	Returned Corrected 'B' No	No to be Scrapped	Scrap label Waster Note Route Card entered
1-9	14	-	-	14	1/2/43 6pm	B XYZ	·	·

CODE TO ABOVE DIMENSIONS, ETC.

Code Letter	Dimension, etc. to be Checked	Mean (Decimalised)	±
A	Length of Thread — ½" ± ·010	·500	·010
B	O/L · 1·125" ± ·010	1·125	·010
C	Thread with Ring & Wickman	·	
D	·030" Radius.	·	
E		·	
F		·	
G			

Checked by H.W.Y.   Recorded by W.L.   Analysed by W.B.K.

NO ALTERATION MAY BE MADE TO THE INFORMATION ON THIS FORM, EXCEPT IN RED BY INSPECTION SUPERVISORS AND MUST BE INITIALLED

Operation Closed by		'B' No		Date & Time		No. off inspected and passed forward	
	(Seg 432) J Blank (Seg 912) R None		XYZ ABC		2/2/43. 2 25pm 3/2/43. 11 30am		318 (Seg 432) 210 (Seg. 912)

Fig. 37 (a). Quality Control Data Sheet (*Front*)

Dimension No. 2. ·045″ $^{+\,\cdot000}_{-\,\cdot006}$

Operating Limits :—Upper ·045 **Mean** ·042 **Lower** ·039
(Decimalised)

'B' No	Check No	Dimensions of Samples 1	2	3	4	Average		Range	Defectives found
B.ABC	1	·040	·042	·042	·042	·041	5	·002	
✓	2	·039	·039	·040	·043	·039	7	·004	
✓	3	·043	·039	·045	·044	·042	7	·006	
✓	4	·043	·042	·041	·042	·042	-	·002	
✓	5	·044	·043	·044	·043	·043	5	·001	
B.XYZ	6	·048	·045	·049	·044	·046	5	·005	7
✓	7	·039	·039	·040	·043	·039	7	·004	
✓	8	·042	·041	·039	·039	·040	2	·003	
✓	9	·043	·044	·039	·044	·042	5	·005	

Dimension No. 3. 3/8 $^{+\,\cdot000}_{-\,\cdot020}$

Operating Limits —Upper ·375 **Mean** ·365 **Lower** ·355
(Decimalised)

Check No.	Dimensions of Samples 1	2	3	4	Average		Range	Defectives found
1	·367	·368	·365	·367	·366	7	·003	
2	·365	·365	·366	·366	·365	5	·001	
3	·366	·365	·366	·366	·365	7	·001	
4	·364	·362	·365	·365	·364	1	·003	
5	·364	·364	·367	·367	·365	8	·003	
6	·366	·366	·367	·366	·366	2	·001	
7	·365	·365	·366	·366	·365	5	·001	
8	·365	·366	·365	·366	·365	5	·001	
9	·367	·366	·365	·365	·365	7	·002	

confirmed by ticking the appropriate column under the code letter of each checked dimension. In measuring samples care must be taken to see that no burrs, etc., exist which would give a false reading on micrometer, vernier calipers, etc.

If *all* samples are within drawing limits, all the parts taken from the machine should be put in the "controlled" bin, and the average dimension ascertained by adding up the recordings for each dimension and dividing the total by the number of samples. This average is to be plotted on the appropriate section of the control chart. Before, however, *any* part is placed in the controlled bin it should be subjected to a quick examination for visible defects such as bad finish, incomplete operation, burring (where called for), etc. The total number of parts, whether within drawing limits or not, taken from the machine at each check is recorded in the appropriate column of the data sheet.

If any one or more of the samples checked are defective in respect of any dimension the setter should be immediately advised and *all* the parts made since the last satisfactory check must be inspected in respect of the incorrect dimensions. Such parts as are satisfactory are placed with the satisfactory work in the controlled bin (subject to visual examination as above), only actual defectives being put in the defective bin.

The recording of the samples in each group will show the dimensions as originally machined; but any recording outside operating limits, and the check number, should be clearly marked by ringing them round, and the number of defectives found shown in the appropriate column.

Parts which are defective in respect of a checked dimension are indicated by ringing round the tick under the code letter of the dimension concerned. The number of defectives found following the 100 per cent. inspection, and the dimensions affected, are indicated in the columns provided.

Defectives should be submitted as soon as possible after they are found, to an inspection supervisor, and never later than the end of the shift on which they were made. The supervisor will decide in which class the defectives fall, namely :—

(1) *Those which can be passed under concession.* These will be placed in the controlled bin (subject to a visual examination) and removed from the tally card; the supervisor making the concession will make the appropriate entry on the data sheet.

(2) *Those which can be passed after further machining, etc.* (*Corrections*). Defectives needing correction will be handed to the setter concerned—with the tally, showing the fault, attached—well before the

end of the shift on which they were made, a note to that effect being made on the data sheet in the appropriate place.

Corrected defectives should be returned with a tally attached before the operation can be closed. *In no circumstances* should an operation be closed with corrections still outstanding, or with any shortage of jobs, unless such shortage is covered by a scrap note and the data sheet and route card shows such fact clearly.

Subject to a re-check of the corrected parts proving satisfactory, the previous entry made on the data sheet is completed by showing the date, etc., on which the parts are returned.

Any entry recorded containing defectives is then rewritten, after the recording of the last check of the order, substituting the dimension of a corrected part for any incorrect dimensions recorded.

(3) *Those which must be scrapped.* Scrap items should be shown to the production chargehand concerned and recorded as corrections if replaceable—except that *in all cases* scrap must be held by the patrol inspector until the end of the operation and then disposed of in accordance with current instructions.

It is important that the sections of the data sheet dealing with the action taken with regard to defectives should be kept up to date.

It is the responsibility of the inspector making a sample check to calculate and record the average dimension on the data sheet, and at once to chart that average on the appropriate section of the control chart. The preparation of the chart, including the insertion of the vertical scale, will be carried out, prior to the commencement of the operation, by separate clerical staff, who will also show drawing limits (in green) and pre-set control limits (in red). Where an operation has *not* been controlled before, the control limit lines will be placed on the chart as soon as possible after the commencement of the operation.

Where all the recordings of any one dimension in a sample group are within operating limits, *but not otherwise*, the average value obtained is plotted as a point on the control chart. Care should be taken to plot points accurately and boldly. Successive points are plotted at one-square intervals as shown on the horizontal scale at the foot of the chart, the numbers of which must correspond with the respective check numbers of the appropriate data sheet.

If any recording is *outside* operating limits, no point is plotted until the defectives have been seen by a supervisor. The immediate action, in such cases, is to draw a vertical line (with the letter "D" above it) on the chart on the line corresponding to the relevant sample check number.

Quality Control Record *A 333	Description: SPECIAL PIN	DRG. No. A 456 B	Issue: 7.	Card No. 1

OP. 1 CONTROL Time Interval = "

Dim No	PARTICULARS	Mean of Opg Limit (decimals)	±	Control Average (decimals)	± Control Limits
1	$\cdot 250'' {}^{+\cdot 000}_{-\cdot 003}$	·2485	·0015	·248	·0005
2	·500" ± ·010	·500	·010	·502	·003

Code Let'r	CHECK PARTICULARS	Mean of Opg Limit (decimals)	±
A	O/L 1 125 $^{+\cdot 020}_{+\cdot 030}$	1·150	·005
B	1/16" Radius		
C	O/D ·750 (bar size) occasionally		

Processed by: J.Y.K.

OP 2 CONTROL Time Interval =

Dim No	PARTICULARS	Mean of Opg Limits (decimals)	± Op Limits	Control Average (decimals)	± Control Limits
1	·185 ± ·005	·185	·005	·185	·002
2	$\cdot 045 {}^{+\cdot 000}_{-\cdot 006}$	·042	·003	·042	·0015
3	3/8" ± ·010	·365	·010	·366	·003

Code Let'r	CHECK PARTICULARS	Mean of Opg Limits (decimals)	±
A	Length of Thread - 1/2" ± ·010	·500	·010
B	O/L - 1 125 ± ·010	1·126	·010
C	Thread with Wickman's Ring	1/4" BSF	
D	·030 Radius		
	NOTE: GOOD FINISH ESSENTIAL ON ·185" DIA.		

Processed by: J.Y.K.

Fig. 38. Quality Control Record

If the defectives are *passed under concession,* the average value as originally measured is plotted on the vertical line already drawn. Where the defectives are *corrected* the average dimension resulting from the substitution of corrected parts for the recorded defectives is applied If the defectives are *scrapped* no point is plotted.

Where orders for the same part follow one another on a machine, without a break, the same chart and data sheet should be used, as control can and should be established just as if one order had been given for the larger amount. (Arrangements are further being made to use charts for successive orders even where a break intervenes.) On the chart, a vertical line is drawn from the top to the bottom at the end of each order, and Main Order No., Sequence No. and No. Off stated on the right of that separating line. The plotting recommences on the first small square following a thick vertical line. This line therefore will apply to sample check No. 1 for the repeat order.

On the data sheet a horizontal line is drawn below the last recording, and Main Order No., Sequence No. and No Off, written immediately below and the recording recommenced.

When an operation is finished, the last items removed from the machine *must be 100 per cent. inspected* Recorded samples should again be, as far as possible, the last to be machined.

The control charts (for sample averages only) for the operational results recorded on the data sheet of Fig 37 are shown in Fig. 39. In the case of the first dimension it will be seen that the pre-set control limits were ignored by the machine setter and that the original setting was too high. Although, over the period covered by the patrol inspector's first eight samples,* the dimensional averages were consistent among themselves—indicating process stability in the theoretical rather than the practical sense—the plotted points were outside the upper control limit. No action was taken, however, until check No. 9 when the machine was re-set and the suspect contents of the controlled bin were subjected to 100 per cent. inspection for this dimension. Of the 136 parts produced during this period 14, i.e., 10 per cent., were found to be oversize and were subsequently corrected. Thereafter this dimension was kept reasonably well in control, although the variation in average dimension had increased as the result of re-setting. (Note that for the first 9 samples the mean range was $\bar{w}=0{\cdot}0023$ in. but that for the remaining 22 samples it had risen to $\bar{w}=0{\cdot}0039$ in.

* Sample check Nos. 2 to 9. Check No. 1, it will be recalled, is recorded by the "first-off" inspector.

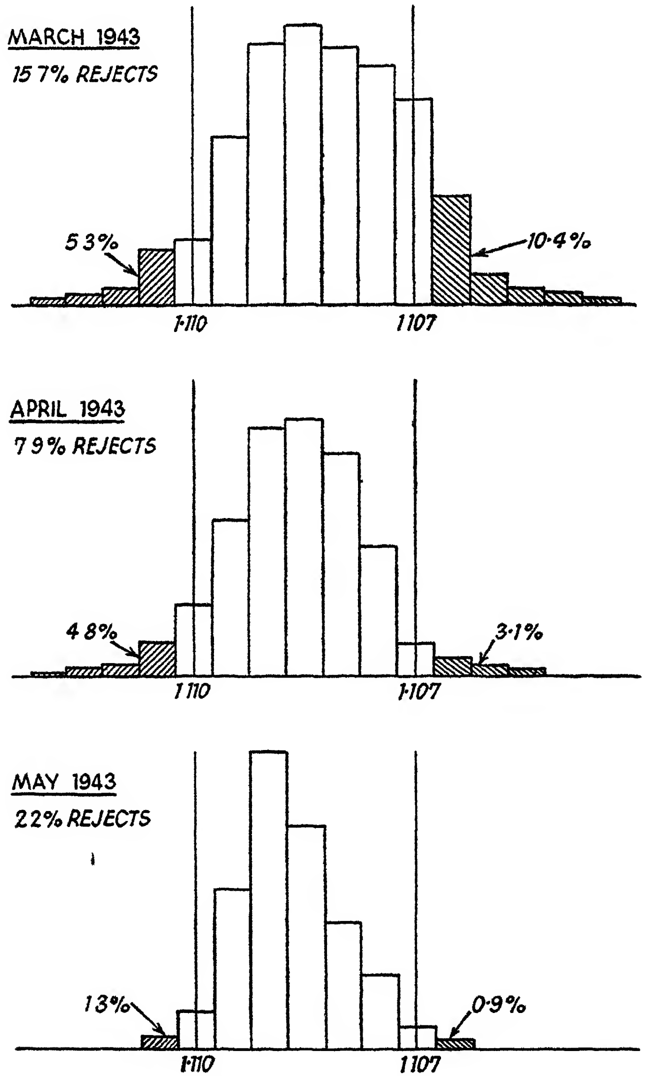
The second dimension was correctly set to the pre-set control limits alculated from a previous batch but, as will be seen, excessive variability oon became evident The fault in this case is most likely to be ascribed o variable raw material, because the fluctuation in sample range is by o means abnormal. (The mean range for all 31 samples works out at $\bar{w}$=0·0032 in for which, with n=4, the upper control limit falls at w=0·0072 in.) Under such conditions the production of defectives is vell-nigh inevitable, calling for 100 per cent. inspection of the product or this particular dimension before passing on to the next operation s indicated by the supervisor's comments at the foot of the data sheet. During the course of patrol inspection, however, only the defectives ound at the 6th sample check on the first batch, and at the 2nd check n the next batch were returned to the setter for correction. t will also be observed that the defectives found at the 14th and 8th check on the first batch, being slightly undersize, were passed nder concession.

A satisfactory control chart resulted in the case of the third dimension. 'he initial setting was correct and tool wear was properly taken care of by e-setting when the need for this was indicated by the chart. The delay 1 the second re-set was in this case not dangerous, since the pre-set control mits were really closer then necessary. (Note that the mean range for ll 31 samples works out at $\bar{w}$=0·0019 in, giving an R.P.I. value of 10, which is far above the critical value for a sample of 4. The appropriate nodified control limits would thus fall at 0·3735 in. and 0·3565 in.)

(c) *Quality Control Supervision.* It may, perhaps, seem unnecessary o stress the importance of adequate supervision of procedure as an essential actor in any quality control system But in point of fact, much depends n how Quality Control is administered by the inspection department; nd success or failure here is often a matter of knowing how far nd when to apply the quality control methods, of deciding which methods o adopt, and of being able to interpret, summarise and convey to others he practical results to be achieved by their use.

In the first place it is not necessary for the inspector-in-charge—or whatever we may choose to call the person responsible for the administration of the quality control system—to have more than a working nowledge of the technical details involved in the construction and maintenance of control charts; such details can be left to the inspection supervisors or foremen and their associated clerical staff. What is vitally important, however, is that he should have a clear understanding of the ims and principles of Quality Control as expressed in the opening three

chapters of the present work ; and that he should be able to translate the operational results of Quality Control in a form that will be readily appreciated by the works management.



QUALITY CONTROL WAS INTRODUCED ON MARCH 23RD

Fig. 40. Reduction in Rejects through Quality Control

In this connection the concept of the *production characteristic* of a machine-shop process has proved—in the author's experience at any rate—to be one of the most valuable contributions to the "getting across" of the quality control idea and its practical applications. It is easy enough to state that the introduction of Quality Control has in three months' time reduced the rate of defective production for a particular job from 16 per cent. to just over 2 per cent. But it is far more convincing, and makes a far more lasting impression, to pictorialise such a statement by means of a series of diagrams showing the successive relations of the production characteristic to the drawing limits, as illustrated by Fig. 40 for the case in question. These diagrams* were actually drawn up from the accumulated inspection records given by the data sheets covering the first three months' operation under Quality Control. The piece part concerned, and the controlled dimension, are depicted in Fig. 41.

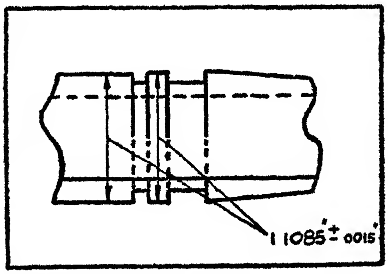


Fig. 41. COMPONENT DIMENSION (AUTO OPERATION)

As far as the immediate supervision of quality control procedures is concerned it must be borne in mind that inspection chargehands and other supervisors, in addition to the exercise of their ordinary supervisory functions, are expected to keep a close general watch on the carrying out of the various instructions covering the quality control of production processes. Among the points demanding proper oversight and careful attention are the following :—

The rules for processing an operation to be controlled must be strictly followed and only departed from with authority from the inspector-in-charge.

If it is agreed that a control process is to be altered, the data sheet and chart alone must be amended. All such amendments must be made in

* In statistical work generally they are known as *histograms*. For their construction see References 3.1 and 3.4 in Appendix A.

red by a supervisor and initialled. This will enable the record card to be altered when the chart, etc., is analysed Amendments should be made by crossing out and re-writing, *not* by alteration.

If a supervisor has any comments to make on a controlled operation either as to the processing, sample interval or the actual machining as recorded, or with regard to concessions he has granted, he should note them in the space provided on the relevant data sheet. These comments will then come to the notice of the inspector-in-charge.

Supervisors responsible for each shift should arrange between themselves so that regular visits are paid to each inspection bench. At each visit the supervisor should —

(1) Examine every chart and instruct patrol inspectors as to any action to be taken.

(2) Note, for his own information, what instructions he has given under (1).

(3) Confirm that any action required on an earlier visit has been taken.

(4) Give instructions with regard to any outstanding defectives

(5) Examine a few specimens from each controlled bin for finish, etc

(6) Examine each data sheet to see that it is being made out correctly and that the section recording action taken with regard to defectives is up to date.

(7) See that the charts and data sheets are correctly placed in racks provided, and are maintained in good order for future use, also collect any completed charts, data sheets, etc.

(*d*) *Co-operation from Production Personnel,* One of the outstanding features—in fact, the main outstanding feature—of Quality Control is that it makes the inspection function become productive and, at the same time, makes the production function become "inspective." In other words, under a system of quality control the inspection personnel get "closer to the job" whilst the production personnel in turn are virtually compelled to take a keener interest in quality *Ultimately, therefore, the success of a quality control organisation is to be measured in terms of the degree of co-operation it induces between the inspection and production departments.* It is not always understood by works management that the responsibility for satisfactory output from a machine shop is shared equally between machine operators and setters on the one hand, and floor inspectors and inspection supervisors on the other hand. Hence it is essential that quality control procedures should take cognizance of the share in that responsibility which devolves upon the production personnel.

With a system of Quality Control, wherever production can be described as " mass production," so close a control can be established over it that, as we have already seen the cause of defective work is largely reduced to mechanical error alone. Where it cannot rightly be described as " mass production," a considerably greater allowance must be made for the

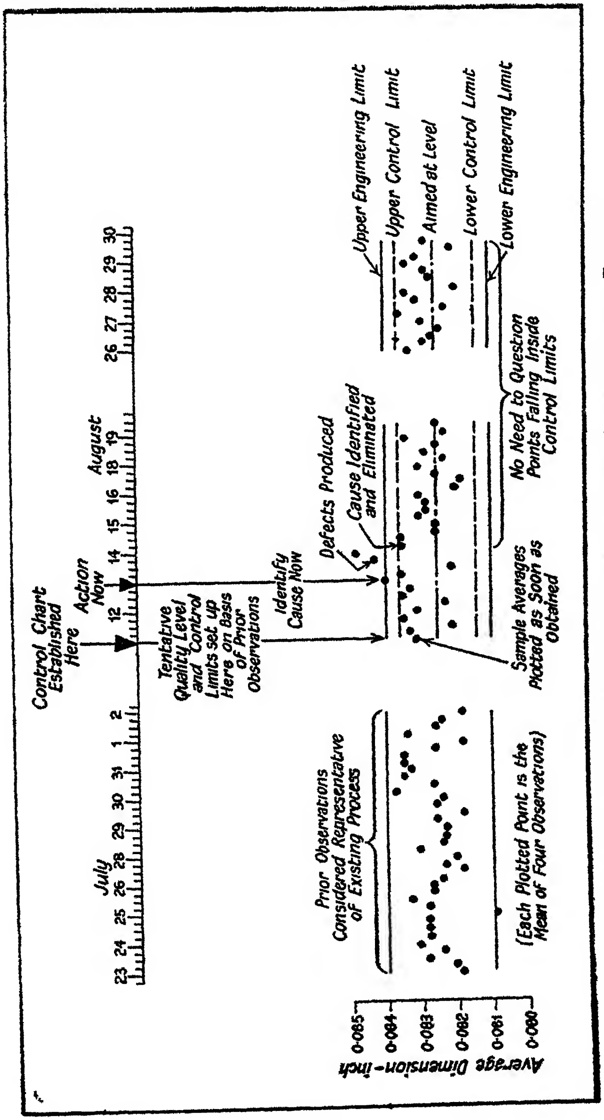


Fig 42. How a Machine sets its own Dimensional Limits

human element in assessing the cause of defective production. Thus the adequate instruction and guidance in the first case of setters, and in the second case of operators as well, is as necessary as that of inspectors to the smooth running of any quality control organisation.

It must be borne in mind, when considering the production point of view, that no system of inspection can avoid the possibility of producing a part outside the drawing limits Quality Control has as its fundamental aim, not the entire absence of defectives (although this *can* be achieved in favourable circumstances), but the reduction of their number to a low and admittedly economic figure. The system is essentially designed to give production personnel advance indication of the tendency for a machine to vary in its performance sufficiently to produce defective work. But if heed is given to such warning, the aimed-at results will be achieved.

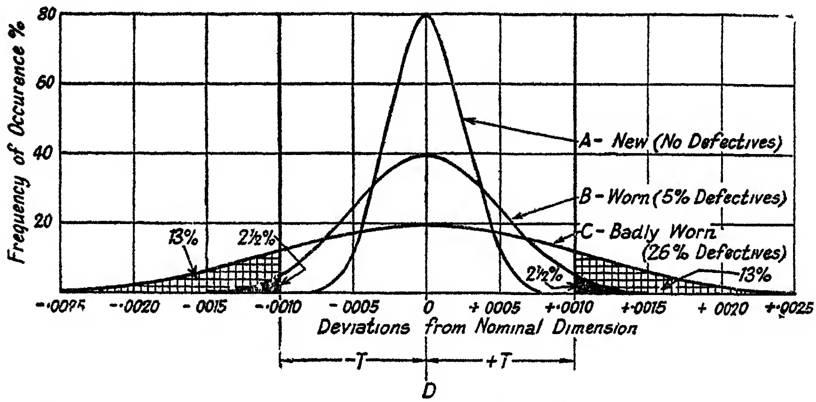


FIG. 43. EFFECT OF MACHINE WEAR ON PRODUCTION OF DEFECTIVES

(1) QUALITY CONTROL AND THE SHOP FOREMAN.* As far as the machine-shop foreman is concerned the system of Quality Control involves the regular checking of samples of the product (*not* single items) as it comes off the machine, and the use of information provided by these samples to disclose the state of the bulk. Recordings are, in fact, made of the important dimension of the part in manufacture and the average dimension is calculated from these recordings. A chart of these sample averages is prepared—the " control chart " for the dimension in question—so that whatever variations there may be can be closely watched. As soon as sufficient recordings have been taken to give a clear picture of the state of

* See also Appendix D, Section 4.

production, what is known as "control limits" are calculated and inserted on the chart. Thus it will be seen that, under a system of Quality Control, *the machine may be said to set its own limits* (see Fig 42).

What these limits are may be explained with the aid of Fig. 43 It will be recalled that under conditions of process stability—the goal of the quality control method—the dimensional pattern of production follows the bell-shaped curve which has been termed the "production characteristic" of the process, three examples of which are shown in the illustration. By proper tool-setting the centre of the production characteristic—the achieved "process average" dimension, $\bar{X}$, that is—can be made to coincide with the nominal dimension or engineering mean, D, half-way between the two drawing limits, $D \pm T$, where $2T$ is the total drawing tolerance.

In Fig. 43, curve "A" shows the production characteristic of, say, a new machine capable of producing work well within the drawing limits specified. As machine wear takes place, the precision of the production process gets less, and the production characteristic spreads out until it overlaps the drawing limits as indicated by curve "B." The areas in the tails of the production characteristic cut off by the drawing limits are then a measure of the percentage of defective product, i.e., parts produced by the process whose dimensions exceed the drawing limits—in this case 5 per cent. If machine wear is allowed to continue until the bearings, slides, etc., become sloppy, the production characteristic will spread out far beyond the drawing limits as indicated by curve "C," where the rate of defective production has risen to 26 per cent.

Although the main purpose of the control chart is to convey immediately an accurate picture of the production process, there is obtainable from the chart, as we saw in Chapter IV, additional information beyond that given by the bare process inspection records. In fact one hopes that in the course of time control-chart technique will come to be recognised, by production engineers and machine-shop foremen alike, as a tool ready to hand for use, as a matter of course, in analysing machine performance, in identifying sources of trouble and, generally, in disclosing the state of production.

(2) Quality Control and the Setter.* Under a system of Quality Control it is more than ever essential for machine setters to co-operate with the floor inspectors, both in the original setting of a machine and in such resetting as may be thought advisable from control chart indications during the run of the job (see Fig. 44).

* See also Appendix D, Section 4.

It is appreciated that this may throw a greater burden of responsibility on to the setters, but unless this burden is cheerfully carried the considerable assistance which the system can give the shop, by reducing scrap and corrections, and to the works as a whole, by a reduction in the total time of machining plus inspection, cannot be obtained.

The original setting of an operation which is not to be controlled or which has not been controlled before, should be as near as possible to the mean dimension—namely, midway between top and bottom drawing limits—tending toward the upper or lower limit according as to whether the dimension is an inside or outside one. This will allow for normal tool wear

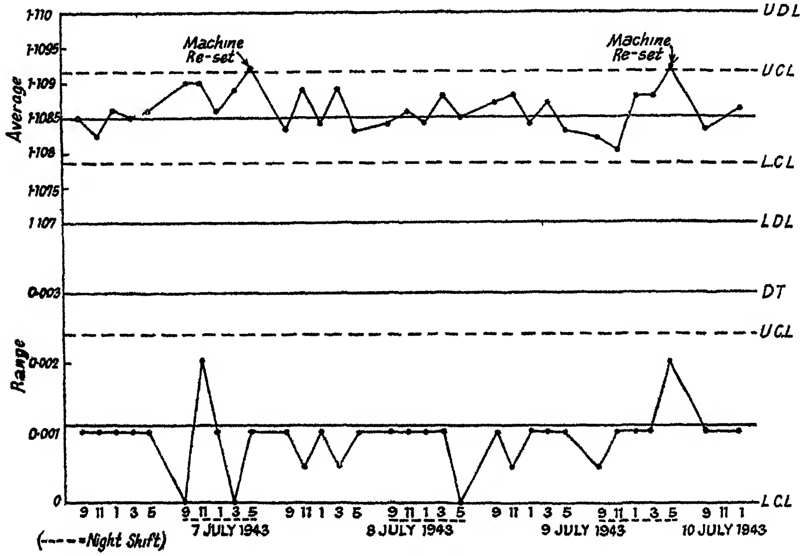


Fig. 44. Control Charts for Average and Range

Wherever an operation has previously been controlled (and of course, as the installation of the system proceeds, the majority of operations will fall in this category) the limits in which the original setting should fall will be indicated to the setter—normally by the first-off inspector.

These limits will be the control limits calculated or decided upon from a previous batch, and the reason for making the original setting within these limits is to reduce, to the minimum, the necessity for further re-settings during the course of the operation.

As the operation proceeds, the control chart will be maintained by the patrol inspector, and the setter concerned will be advised as soon as

this chart shows that the dimension concerned is being produced outside control limits If action is taken to bring such dimensions back within control limits straight away, the setter will assist, not only himself, by avoiding corrections, but production as a whole, by removing the necessity for full 100 per cent. inspection (see Fig. 44). If, on the other hand, no action is taken when the warning is given by the control limits, the chances of defectives being produced, which will require further machining or which may even be scrapped, are very greatly increased.

Control limits will be spaced as widely as possible, consistent with safety, but if action is not taken to keep within these limits, the benefits of Quality Control will be lost and correction time and/or scrap can only result. *Where machine setters are concerned the importance of this procedure cannot be too strongly emphasised.*

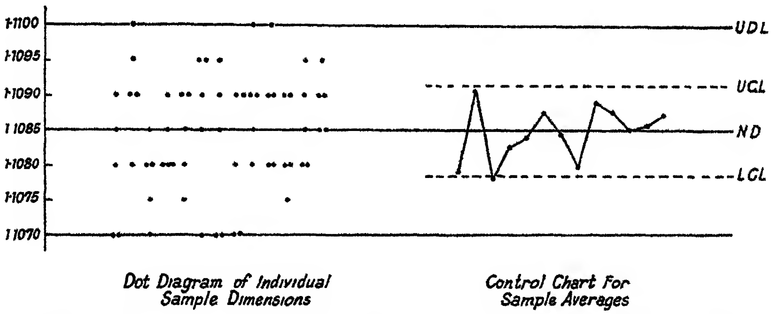


Fig. 45. Relation between Individual and Average Dimensions

In this connection it must be remembered that the plotted points on the control chart represent the average dimension of a group or sample of piece parts. By taking the average dimension of several parts, rather than the single value given by only one part, one obtains a much truer picture of the product from which the sample was taken. When examining a single part one may have hit upon a freak which is not truly representative of the bulk. The control chart therefore provides a more definite indication of the general trend of the production process at the time of the sample check than would a chart drawn from the individual dimensions. This is illustrated by Fig. 45, which, like Fig. 44, refers to the dimension depicted in Fig. 41. The "dot diagram" of the individual dimensions ($n=5$) is shown on the left and the corresponding control chart for sample averages on the right.

The drawing or process (operating) limits and the control limits are shown on the control chart. If, during the entire operation, only a small

number of plotted points fall outside the control limits, it can be assumed with safety that the bulk product will fall within the operating limits—providing that the control limits are fairly evenly spaced within the operating limits, and that the relation between these limits (called the "contro ratio"), satisfies given percentages based on the number of piece parts in each sample.

So far as the control limits are concerned it should be borne in mind that there is no intention to impose closer limits than drawing or process limits on the *finished* product. Even though the samples taken during the entire run may be within *control* limits, a 100 per cent. inspection of the bulk product would almost certainly disclose the fact that a number of parts were outside such *control* limits ; but owing to the manner in which the control limits are set, only a negligible percentage can be outside the *operating* limits. For the purposes of this system, any part which does not entirely conform to drawing or process limits is termed a "defective." (This does not mean that the part is necessarily useless.)

(3) Quality Control and the Operator.* In the case of semi-automatic processes (e.g., capstan turning, milling) the operator exercises a major influence on the precision of the job and thus on the ability of the machine to meet the specified drawing limits (*cf.* Fig. 43) This influence, too, is apt to be spasmodic rather than regular—as in the case of machine wear in an automatic screw machine or press—and hence it is essential that the operator should be made to understand the part he or she has to play in any system of Quality Control. Besides, from the practical point of view, it is almost impossible to eliminate the operator's effect on the precision of the production process unless rather elaborate precautions are taken, such as the provision of a dial indicator on a capstan stop. Therefore, a simple explanation like the following "message to the machine operator", issued by one firm during the war years as part of its routine quality control instructions, is likely to prove helpful in promoting a co-operative attitude amongst machine-shop personnel :—

You may ask yourself the question : "Why should I take any interest in Quality Control?" The answer is that when Quality Control can be applied to the job you are doing it is a valuable aid to the production of good work, and since *only* good work is of any use in furthering the war effort, it is clear that the subject should interest you equally with the setter, the floor inspector and the shop foreman. So far as you are concerned, the chart over your machine will tell you if the work you are

* See also Appendix D, Section 5.

turning out is uniformly correct in respect of some important dimension which is shown on the chart

Let us take as a simple example the case of a capstan job with which you are familiar, and where you are asked to maintain a particular dimension within certain " high " and " low " limits.

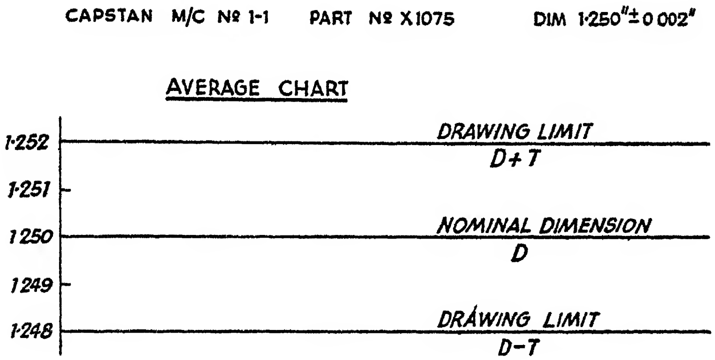


Fig. 46. Drawing Limits on " Average " Chart

Here the important dimension is 1·250 in. It is not, of course, possible to make every part exactly to this measurement, so the production engineer makes, in this case, an allowance of two-thousandths (0 002 in) above and below the nominal dimension These lines are marked on the chart, and are called the *drawing limits*

Then, by a known calculation that you need not bother about, the inspection department add two dotted lines to your chart, like this.

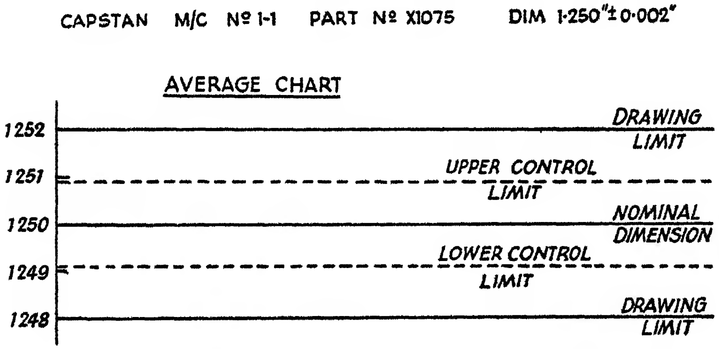


Fig. 47. Control Limits added to Chart of Fig. 46

These dotted lines are called the *control limits*. As you work is checked by the floor inspector, a dot is placed on the chart to indicate the average of his measurements. After some time the chart will look something like this:

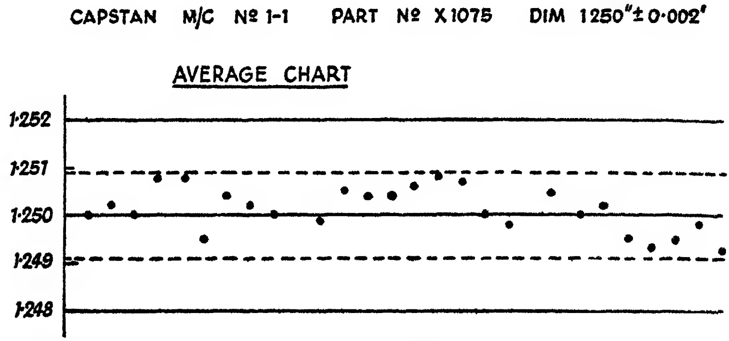


Fig. 48. "Average" Points Plotted on Chart of Fig. 47

When all the dots lie inside the control limits everything is all right, and the parts you are making will be within the all-important drawing limits. But if dots begin to appear either above or below the control limits, as shown at "A" in the following chart—

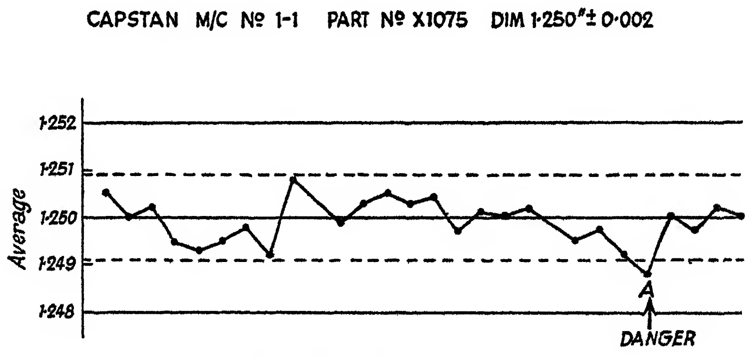


Fig. 49. The Completed Control Chart

then there is danger that you may be turning out defective work. It means that you will have to exercise greater care in operating your machine or, perhaps, that some action is required by the setter.

This is really all you need to know about Quality Control. If you are interested in watching the chart, remember any dots *outside* the control

limits are warning signals indicating that trouble is approaching, with all the bother of having to repair or even junk the work you are doing.

Remember that action taken in time will not only avoid waste of effort and material, but will also increase effective production. When in doubt consult your floor inspector, he is there to help you turn out good work.

Routines Based on the Method of Defectives. It is pretty obvious from a comparison of the contents of Chapters IV and V that a system of Quality Control based on counting defectives is far easier to introduce, and to "get across" to inspection and production personnel, than is any system based on dimensional measurement. For this reason the method of

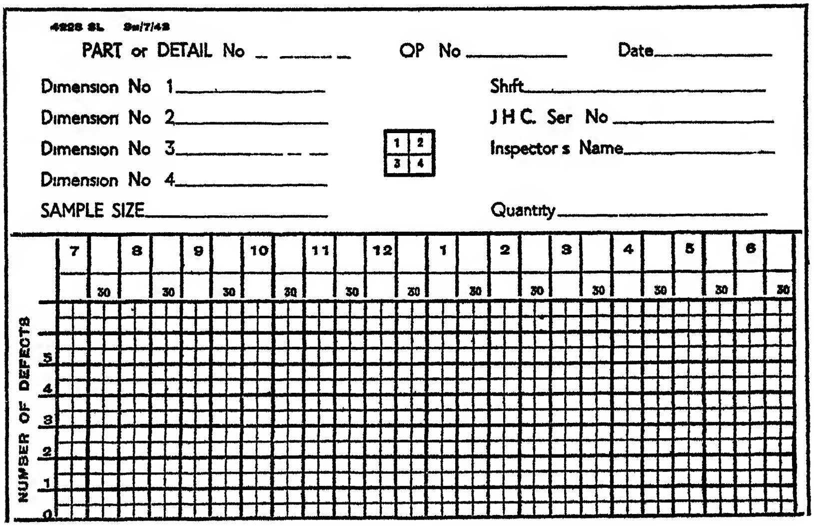


Fig. 50. A Simple Defectives Data Sheet

defectives is often favoured by production engineering firms, in spite of its lack of sensitivity and of the paucity of engineering information which it provides. Another advantage of this simple method of Quality Control is that its application is not restricted to dimensional measurements (through the use of limit gauges, of course) but extends to non-measurable quality characteristics such as colour, finish, and other similar attributes inspected by purely visual means.

As far as dimensional control is concerned, the routine to be followed in maintaining charts for number defective c is much the same as for charts for sample average $\bar{x}$ and range w. Fig. 50 shows a typical data

sheet covering four separate dimensions and values of c from 0 to 5 in a sample of n. The inset diagram (containing the four numbered squares) is a reminder to the patrol inspector as to which of the four small squares, corresponding to a given number defective and a given inspection time, should be blacked in for the dimension being checked. An inspection interval of 30 minutes has been chosen as standard in this example. If more than five defectives are found in a sample, the number "c" is itself written in the appropriate small square in the top row of the data sheet Charts for number defective can then be kept either for each dimension separately, or else for all four dimensions jointly.

A more elaborate type of data sheet for number defective is illustrated in Fig. 51*. The upper part records the number of defectives found outside the upper (+) and lower (−) drawing limits for each of up to seven different dimensions The middle section of the data sheet constitutes the control chart for total number defective, i.e., the number of defective piece parts—some of which may be defective in respect of more than one dimension—found in the sample of size n. The lower part gives details of interest to production and progress personnel on the action taken with regard to the defective items found after 100 per cent. inspection of the suspect bulk product collected for the machine at the time of sampling inspection.

As simple and convenient a standard data sheet as any on which to record and chart the sampling inspection results in the case of multi-dimensional and visual checks is that illustrated in Fig. 52, a description of which was given in connection with the example of Fig. 23. This form of combined process inspection record and control chart is being very widely used throughout one large manufacturing concern. The number of separate jobs being controlled in this manner already runs into four figures. Provided all work produced during the preceding inspection interval is 100 per cent. inspected (and cleared of defectives) whenever a point on the chart reaches either the "warning" or the "action" limit, the control chart can be used to estimate the rate of defective production during the run of the job. In this particular case a total of 14 distinct defectives were found in 48 samples of 8 components each, so that the achieved process average was

$$\bar{p}=\frac{100\times 14}{48\times 8}=3{\cdot}64 \text{ per cent. defective.}$$

These "operational charts" are hung on boards over the machines

* As used by the Bristol Aeroplane Company in its extensive quality control organisation.

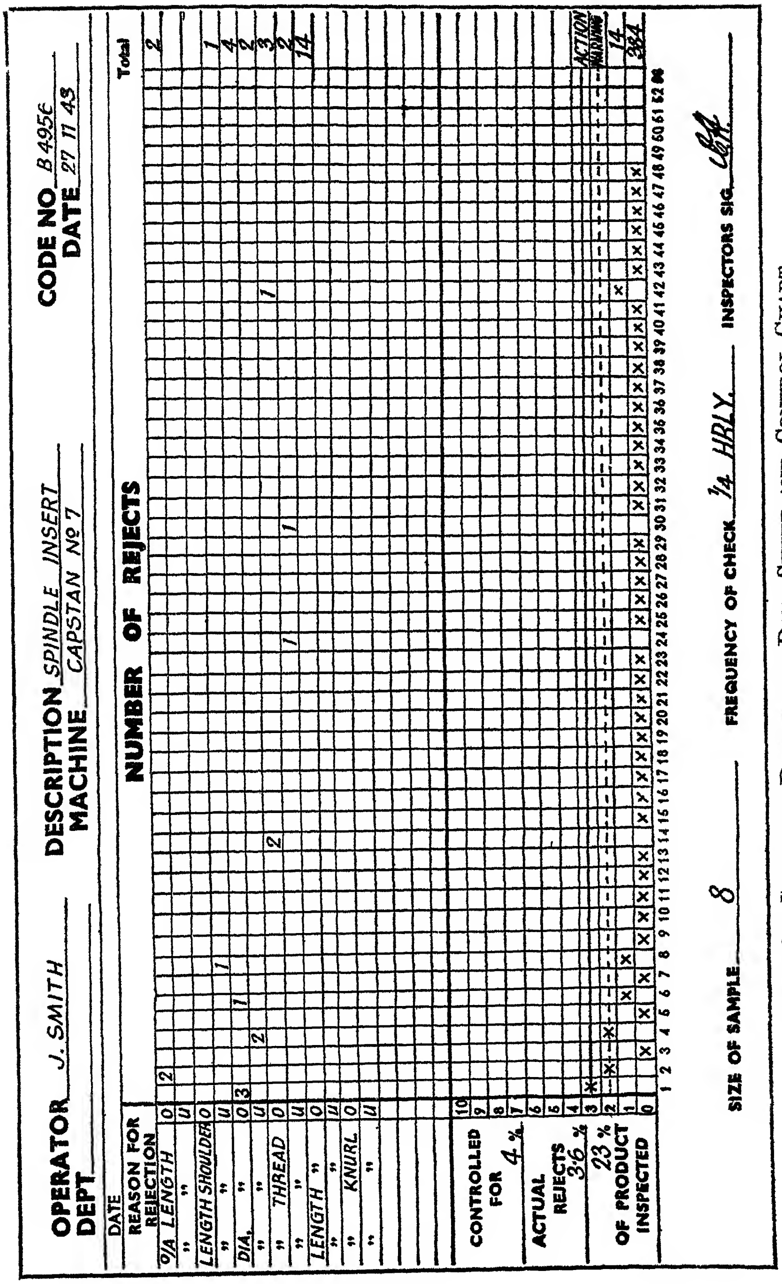


Fig. 52. Combined Defectives Data Sheet and Control Chart

concerned and so-called "master charts" are kept on the reverse side, whose purpose is to show the change in the process average $\bar{p}$ day by day or, more usually, week by week. Fig 53 shows the weekly record of the job charted in Fig. 52. The aimed-at values (i e, the control levels) are indicated by the dotted lines. It will be seen that as the result of first nine weeks' operation under Quality Control the control level was revised from $\bar{p}=5$ to $\bar{p}=4$ per cent. defective Whenever any sharp set-back is observed on the master chart the cause of such increase in process average $\bar{p}$ is indicated on the chart by appropriate code letters.

The advantages of such operational and master charts for showing the current rate of defective production and its relation to previous figures are obvious. In a large manufacturing department it is clearly impossible for the foreman or shop superintendent to be fully informed as to the hour to hour performance of his operators. But with the aid of charts like those of Figs. 51 and 52 he can see at a glance how each employee is working at the moment, and can compare the current standard of his or her work with that of the preceding weeks. This is highly desirable, if not essential, where new operators are constantly being brought into a section or department Furthermore, such simple charted records are of the greatest value not only to inspection and production personnel, but also to the planning, design and even purchasing departments since they indicate how material is varying, when machine difficulties arise, and what other impediments are obstructing the smooth progress of any particular job.

Quality Bonus Systems. A powerful aid in promoting a correct factory attitude to the general quality problem is the use of quality incentives. A widely practised method of developing quality-mindedness among machine-shop operatives is to have defective work sorted or repaired by the operatives responsible in their own time. However, in formulating any plan embodying a quality incentive, it is better psychology to state the incentive as a bonus for good work rather than as a penalty for bad work Unfortunately, the use of a bonus proportioned to the quality of the work is by no means as extensive in industry as the use of a bonus for higher output. It is the author's belief that here there is a fertile field waiting to be tilled by industrial engineering effort, for there are many process operations wherein the manufacturing loss due to poor quality is of the same or even greater order of magnitude than the value of the labour required to perform the operation. The advent of quality control methods and, in particular, the control chart for fraction or number

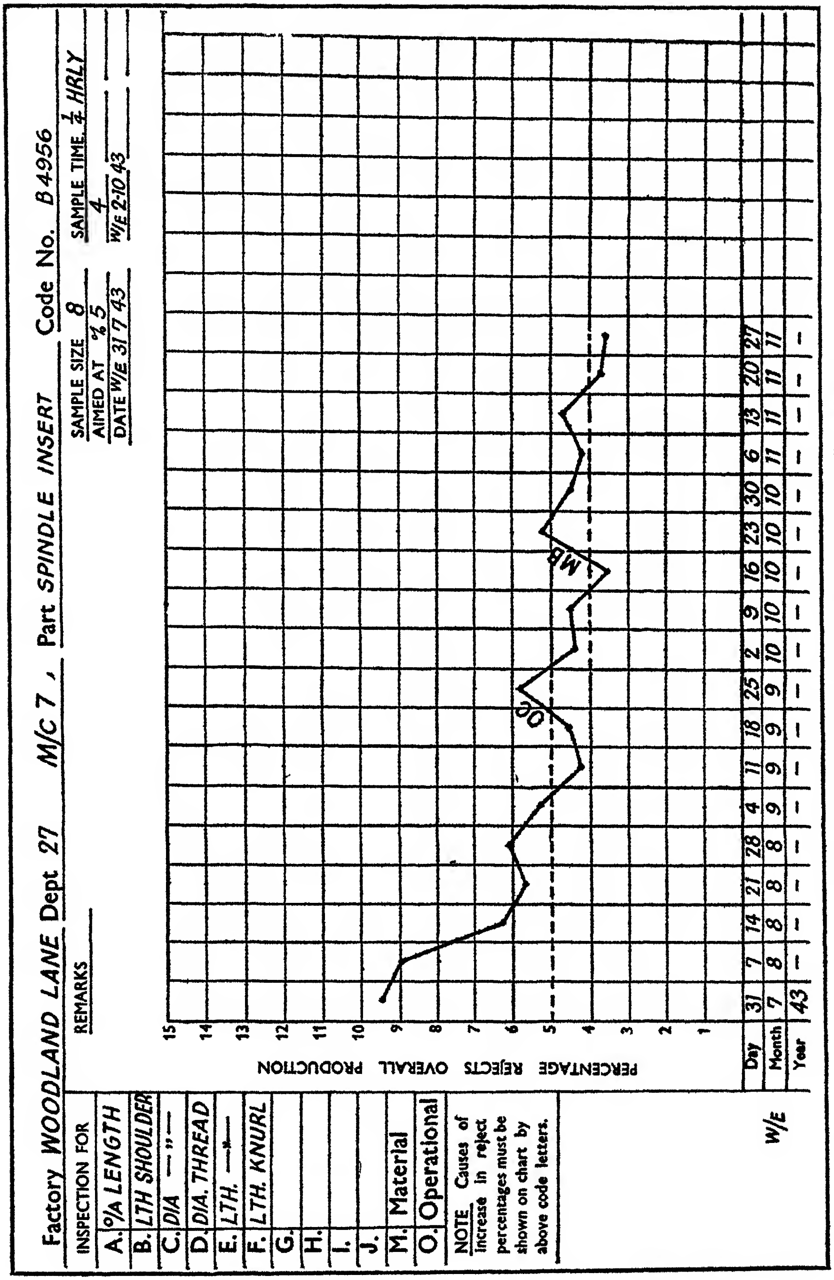


Fig. 53. Percentage Rejects Control Summary

defective, has quite recently led to the development of quality bonus systems as a means of improving product quality.

An example of such a bonus system in the case of a manual process, which may serve as an illustration of the way in which a control chart can effect a really marked improvement in product quality, is that associated with Fig 54. This particular control chart relates to one of a group of operators engaged on resistance grinding and covers a period of two weeks during which the quality bonus system was first introduced The quality level of this group had for a long time averaged some 15 per cent defective before the introduction of Quality Control To begin with

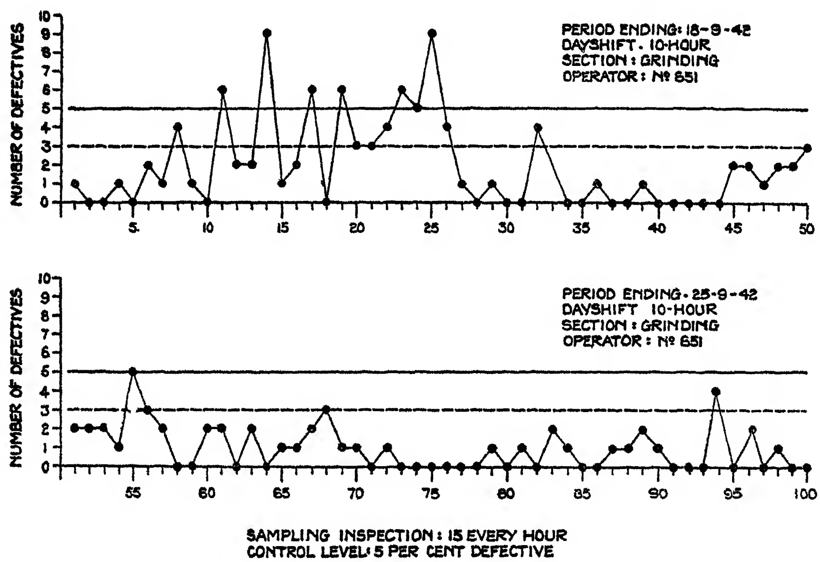


Fig. 54. CONTROL CHART FOR A MANUAL OPERATION BEFORE AND AFTER INTRODUCING QUALITY BONUS

the individual operators' quality variations were plotted without giving the operators any explanation as to the meaning of the control charts, which were placed on the machines. A control level of 5 per cent. defective was chosen as being an economic standard for this particular production process, this level being the same for all the operators

Halfway through the first week the operators were told about the impending quality bonus scheme, which was as follows : For every point

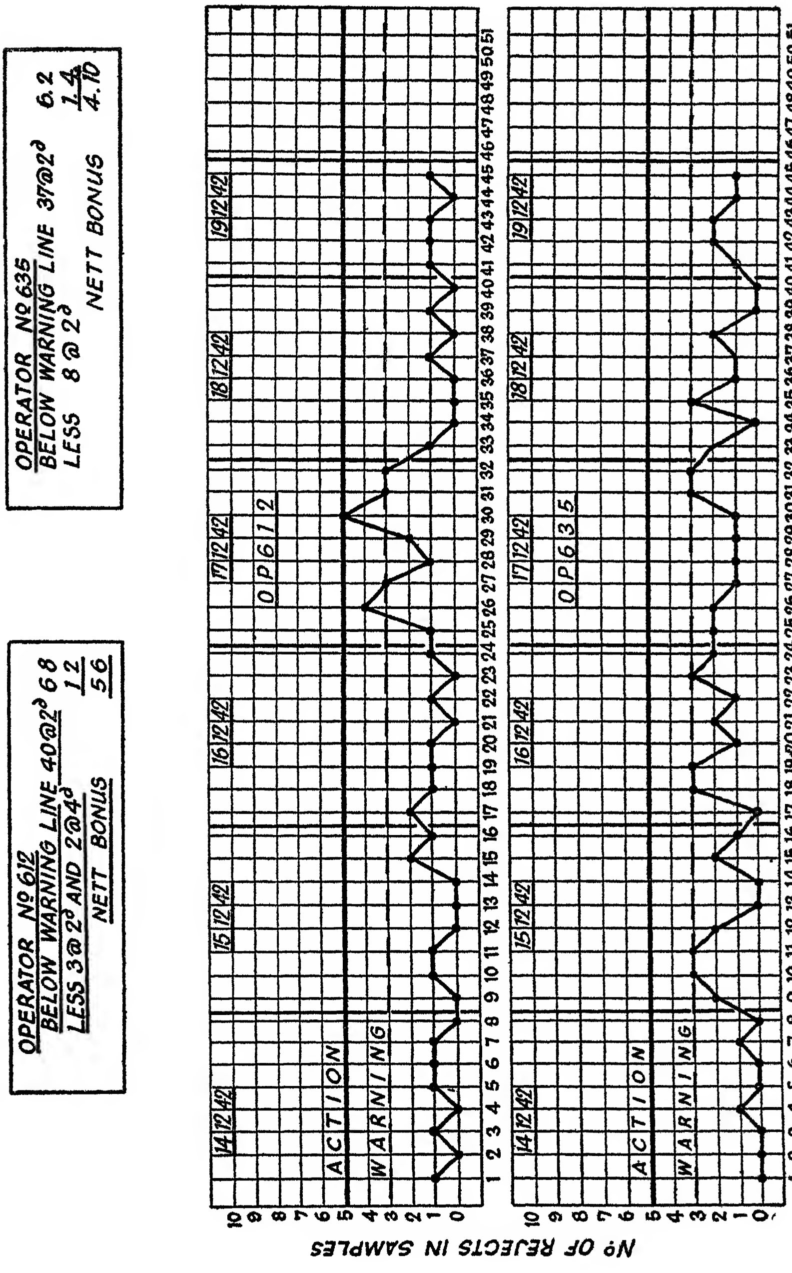


Fig. 55. Control Charts for two Operators Working under Quality Bonus Conditions

on the chart below the dotted line (warning limit) each operator would receive 1d.; for every point on the dotted line 1d. would be deducted; and for every point above the dotted line 2d. would be deducted. But in no case would such deductions (if in sum they came to exceed the aggregate bonus) be made from the normal piece-rate earnings The effect of this information is at once apparent from the case depicted in Fig. 54 During the first half of the initial week the operator averaged 20 per cent. defective, during the latter half of the week this average fell to 6 per cent. The quality bonus scheme actually came into force in the following week (lower part of Fig. 54), during the course of which the operator successfully maintained an average of just over 6 per cent.

Those who have had experience with simple quality bonus systems of this type are surprised how operators engaged on jobs where manual skill is required soon learn to avoid the "warning" limit on the control chart Under such circumstances one may be tempted to reduce the control level below the standard rate of defective production originally set. To do so, however, is unwise as it would penalise the average operator at the expense of the exceptional performer. *The same argument applies here as in the case of setting standard times as a basis for piecework rates* Very great care is required in establishing an equitable and at the same time an economic standard of quality. In the example already quoted, the control level of $\bar{p}=5$ per cent. defective was decided upon after an extensive analysis of past records supplemented by experimental control-chart data After some months' experience with this quality bonus system, no valid reason could be found for revising the quality standard, but the bonus scale was altered by doubling the bonus and penalty figures so as to attain a better incentive—a factor of some importance in a section of 22 operators showing varied levels of skill.

The results in the case of two average operators are illustrated by the control charts of Fig. 55. At the end of the week the first operator had achieved a process average:

$$\bar{p}=\frac{100\times 46}{45\times 15}=6\ 8 \text{ per cent.},$$

whilst the second operator had attained the value

$$\bar{p}=\frac{100\times 60}{45\times 15}=8{\cdot}9 \text{ per cent.}$$

Their respective quality bonus earnings were 5s. 6d. and 4s. 10d. for the week. The maximum bonus payable in this case was 7s. 6d., so that a sufficient margin of incentive exists to prompt an improvement towards

the standard quality level of 5 per cent. defective. Since the revision of the quality bonus scale the section average has fallen to this aimed-at level and the operators have been earning a quality bonus of 5s. per week on the average, over and above their ordinary production bonus. A similar quality bonus system has recently been introduced with considerable success among capstan operatives in a machine shop, and it looks as if this new development in quality control technique is going to have a considerable future in production engineering.

EPILOGUE

By way of conclusion to a work dealing in the main with the practical applications of quality control methods to production engineering it may prove helpful to consider once more the essential nature of this new technique—the statistical method of controlling product quality during manufacture. For instance, the following statement, which appeared in a widely-read journal devoted to production engineering matters,* provides an almost perfect example of what Quality Control is *not*

> " Control of quality by statistics is the recording of the actual fluctuations in the dimensions of the product of the machines, and the statistics so compiled are then available for future guidance. . . ."

The author of this statement clearly failed to grasp the fact that the quality control chart is essentially news and *not* history. This is evident from his further comment, that " quality control charts and records can only serve a useful purpose . . . by having as their object the reduction of scrap material and wastage of time, but as the chart is recorded after the event, it is difficult to understand how even this would be achieved."

The outstanding and characteristic feature of the quality control chart is its practical value as a signalling device, indicating to all concerned the onset of impending trouble, and providing objective evidence upon which the appropriate preventive measures may be based. Perhaps the best definition of Quality Control is that *it puts process inspection on a sound basis*. For, in the last analysis, the technique of Quality Control is an inspection technique—one which makes the inspector's function active and productive, instead of passive and non-productive. To quote an authority on this subject :†

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* "Is Quality Control by Statistical Methods Justified ?"—*Machinery*, 4th February, 1943, p, 119.

† H. F. Dodge: "Using Inspection Data to Control Quality," *Manufacturing Industries*, December 1938, p. 615.

"Inspection is valuable as a measuring instrument when used solely for the purpose of separating the bad product from the good. But its greatest value and fundamental purpose is to provide information that will assist in controlling quality."

This is borne out by the views, expressed some time ago to the author, by the chief inspector of the manufacturing concern which was the first in this country to introduce Quality Control into its machine shop. Upon being asked the question: "Has Quality Control assisted production?" his reply was: "Undoubtedly, yes." He then went on to say that, apart from the question of minimising the creation of defective work, the following important benefits had been obtained which in themselves have more than justified the introduction of the system:—

(1) The control charts provide factual evidence of the running of the jobs to which they relate. This evidence has proved invaluable in determining the root causes of trouble, e.g., faulty tooling, machine wear, difficulties imposed by design, etc

(2) Such evidence has enabled the chief inspector to issue frequent reports on the difficulties encountered with specific jobs, on the condition of machines, etc., which have enabled the planning department to take immediate action before production has to be held up.

(3) Furthermore, on the evidence of control charts it is possible to advise the design department whether or not, in any particular case, it is possible to work to certain narrower drawing limits if that should become necessary at any time.

(4) The use of control charts in the machine shop, where they can be seen and studied by inspectors, tool-setters, and operatives alike, has made for closer co-operation between the inspection and production organisations.

This last benefit is, in the long run, the most important of all. One of the conclusions reached by the Select Committee on National Expenditure in its 49th Report (*An investigation into certain complaints regarding two Royal Ordnance factories*—14th May, 1942) was that "means should be found to overcome the latent rivalry which exists between inspectors and operatives." In the method of Quality Control we have such a means ready to hand, and industry to-day is at last becoming alive to the fact.

APPENDIX A

SELECTED LITERATURE ON QUALITY CONTROL AND ITS APPLICATIONS

(1) REFERENCE HANDBOOKS.

1 1 *B S* 600R-1942 *Quality Control Charts*, by B. P. Dudding and W J. Jennett (British Standards Institution, 1942)

A booklet emphasising the statistical background of Quality Control, but giving complete information on the setting up and interpretation of industrial control charts.

1.2 *Quality Control Methods when Manufacturing to a Specification*, by B P. Dudding and W J. Jennett. (G.E.C. Research Laboratories, London, 1944.)

This booklet may be looked upon as a sequel to *B.S.* 600*R*-1942 in that it develops the application of the "relative precision index" theory to Quality Control. The earlier literature (e g., *B S.* 1008 and *B S.* 600*R*) takes no account of the practical need of meeting "manufacturing limits."

1 3 *Quality through Statistics*, by A. S. Wharton. (Philips Lamps Ltd., London, 1945.)

A useful all-round introduction to the uses of quality control and acceptance control methods in the factory, with the emphasis on methods based on counting defectives.

1.4 *An Engineer's Manual of Statistical Methods*, by L. E. Simon. (Chapman and Hall, London, 1941)

Written mainly from the standpoint of ordnance inspection in the U.S.A., but valuable as a general guide to the use of sampling inspection procedures for the Quality Control of production processes, as well as for the quality determination of the resulting products

1 5 *Economic Control of Quality of Manufactured Product*, by W. A. Shewhart. (Macmillan, London, 1931.)

The standard textbook on the subject by the founder of Quality Control technique. Although largely theoretical in treatment and philosophical in tone it amply repays careful study, particularly after some experience with quality control applications.

(2) PUBLICATIONS DEALING WITH PRODUCTION APPLICATIONS

2 1 *A First Guide to Quality Control for Engineers*, by E H. Sealy. (H.M. Stationery Office, 1943)

A booklet issued by the Advisory Service on Quality Control of the Ministry of Supply and giving full details on the setting up and interpretation of Quality Control charts based on dimensional measurement. It includes a section on the so-called *group control chart* for multi-spindle autos.

2 2 " Quality Control in Production Engineering," by H. Rissik. (Reprinted from *Aircraft Engineering*, February-April, 1943. Bunhill Publications, Ltd., 12, Bloomsbury Square, London, W.C.1.)

A reasonably complete explanation of the quality control method as applied to production engineering. The first part (February, pp. 55-58) is introductory and describes the aims, results and basic principles of the method. The second part (March, pp. 85-90) deals with applications of the method based on dimensional measurement The third and final part (April, pp. 93, 115-119 and 121) discusses applications of the method based on the use of limit gauges, and answers some common criticisms of Quality Control as a machine-shop aid.

2.3 *The B.A.C. Quality Control Handbook.* (The Bristol Aeroplane Company, Ltd., Filton, Bristol, 1943.)

A practical handbook giving a résumé of the various instructions issued to the Aircraft Division Machine Shop on the applications of Quality Control to its production processes, and setting out the duties of all personnel connected either directly or indirectly with the system.

2.4 " Quality Control," by W. A. Bennett and J. W. Rodgers. (*Aircraft Production*, April, 1943.)

An article outlining a particular application of the quality control method appropriate to fast auto-production of components, involving the simultaneous control of many dimensions together with visual defects.

2.5 " Modern Applications of Quality Control Methods," by A. S. Wharton. (*Industry Illustrated*, March, 1943.)

An article describing in general terms the method of Quality Control based on the use of limit gauges, and its application to quality bonus systems of wage incentive.

2.6 " The Technique of Quality Control." (*The Engineer*, 30th January, 1942)

This article is written around an appendix to Lieut -Col. Simon's book (see *Reference* 1.4 above), giving details of a typical set of instructions for routine Quality Control procedure in an ordnance factory.

2 7 " Sampling Inspection and Quality Determination," by H. Rissik. (Reprinted from *Aircraft Engineering*, May and June, 1943. See *Reference* 2.2 above)

A general account of the statistical method of setting up sampling inspection procedures as practical and economic alternatives to the usual 100 per cent. inspection of components and other similar products supplied in bulk.

2 8 "Practical Applications of Quality Control," by W. A Bennett and J. W. Rodgers. (*Machinery*, Vol. 63, 23rd December, 1943, p 701, and 30th December, 1943, p 737.)

An article describing the methods and procedures for Quality Control in mass production.

2 9 *Symposium of Papers on Statistical Quality Control.* (Ministry of Production, C.M.L Buildings, Great Charles Street, Birmingham, 1944.)

A series of lectures given under the auspices of the Quality Control Panel of the Ministry of Production's Birmingham District Production Committee

(3) PUBLICATIONS DEALING WITH THE STATISTICAL BACKGROUND TO QUALITY CONTROL.

3.1 *A.S T.M Manual on Presentation of Data.* (The American Society of Testing Materials, 260, South Broad Street, Philadelphia. 4th Edition, March, 1941)

This booklet, which constitutes quite the best possible introduction to the statistical interpretation of numerical data, is available through the British Standards Institution, 28, Victoria Street, London, S.W.1.

3.2 "Sampling Inspection and Quality Control," by B. P. Dudding. (*Journal of the Institution of Production Engineers*, 1943, Vol. 19, pp. 1-50.)

An important paper, giving a general account of the statistical basis of Quality Control, followed by an equally informative discussion

3.3 "The Efficient Use of Gauges in Quality Control," by L. H. C. Tippett. (*The Engineer*, 23rd June, 1944.)

An article describing one of the few really important developments that have taken place in quality control technique as applied to machine-shop practice, namely, the use of the method of defectives as an efficient substitute for the more widely publicised method of measurement.

3.4 "Probability Graph Paper and its Engineering Application," by H. Rissik. (*The Engineer*, 24th and 31st October, 1941.)

An article discussing in an elementary manner the statistical method of presenting and interpreting numerical data (e g., test results, inspection records) and describing a graphical procedure for plotting such data so as to obtain a maximum of useful information with a minimum of calculation. This graphical method has been widely used as a means of quality supervision in the Royal Ordnance Factories.

3.5 *Statistical Methods in Industry*, by L. H. C. Tippett. (Iron and Steel Industrial Research Council, London, 1943.)

This booklet is a reprint of several lectures, given by a leading industrial statistician, at Sheffield University during the summer of 1942. It is by far the best general introduction to the industrial applications of statistical methods (including Quality Control) which has so far been published.

3.6 "Model Quality Control Charts," by H. Rissik. (*The Engineer*, 24th and 31st July, and 7th August, 1942.)

An article describing the construction and use of model charts as aids to practical instruction in quality control technique.

(4) LITERATURE OF GENERAL INTEREST.

4.1 *Proceedings of the Institution of Mechanical Engineers*, Vol. 147, No. 3 (June, 1942), pp. 125-144.

Report of the London Engineering Conference on Quality Control held on 15th April, 1942. (See also a leading article in *The Times* for 16th April, 1942, entitled "Speeding Production.")

4.2 " A Pioneering Achievement in Quality Control," by H. Rissik. (*Machinery*, 13th August, 1942.)

An article giving a brief account of the first application of quality control technique to machine-shop production in this country.

4.3 " Statistics and Engineering Practice," by B. P. Dudding and W. J. Jennett. (*I.E.E. Journal*, 1940, Vol. 87, pp. 1-21.)

A paper describing and illustrating the application of modern statistical methods to certain engineering problems.

4.4 " Quality Control and the War," by Lieut.-Col. L. E. Simon (*Electrical Engineering*, September, 1942.)

A paper presented by authority of the Chief of Ordnance at the Amer.I.E.E. Convention on 1st May, 1942.)

4.5 " Quality Control Procedures in Ordnance Inspection," by G. D. Edwards. (*Engineering Inspection*, 1943, Vol. 8, No. 2.)

Reprint of a paper by the Consultant on Quality Control, U.S. War Department, and presented by the Production Engineering Division of the Amer. Soc. Mech. Eng. at the semi-annual meeting held on 8th-10th June, 1942.

4.6 " Statistical Methods in Engineering Practice," by H. Rissik. (*The Engineer*, 30th November, 6th, 13th, 20th and 27th December, 1940.)

An article surveying in a practical manner some of the ways in which statistical methods can help the engineering manufacturer in design, production and inspection.

4.7 *Statistics*, by L. H. C. Tippett. (Oxford University Press, 1943.)

A new volume in the " Home University Library " series giving an excellent, popular account of statistics as a branch of scientific thought and method.

APPENDIX B

CONTROL CHART DATA

Tables VII and VIII give the necessary factors for arriving at the control limits for the average and range charts, and the stability limits for the production characteristic, in the case of Quality Control by dimensional measurement, as described in Chapter IV. Charts I and II show the control limits for number defective, appropriate to Quality Control by counting defectives, as explained in Chapter V.

TABLE VII

CONTROL LIMITS AND STABILITY LIMITS

Sample Size	Average Chart		Range Chart		Production Characteristic	
	Standard Limits $\bar{X} \pm A\bar{w}$	Modified Limits $\bar{X} \pm (T - E\bar{w})$	Upper Limit $D\bar{w}$	Lower Limit $D'\bar{w}$	Standard Deviation $\sigma = F\bar{w}$	Stability Limits $\bar{X} \pm G\bar{w}$
n	A	E	D	D'	F	G
2	1·94	0·80	3·52	0·01	0·89	2·66
3	1·05	0·77	2·58	0·10	0·59	1·77
4	0·75	0·75	2·26	0·19	0·49	1·46
5	0·59	0·73	2·09	0·25	0·43	1·29
6	0·50	0·72	1·97	0·31	0·40	1·19
7	0·43	0·71	1·90	0·35	0·37	1·11
8	0·38	0·70	1·84	0·39	0·35	1·05
9	0·35	0·69	1·79	0·42	0·34	1·01
10	0·32	0·69	1·76	0·44	0·32	0·97

$\bar{X}$ = Aimed-at dimension (process average).

$2T$ = Drawing tolerance $\quad \bar{X} \pm T$ = Drawing limits.

TABLE VIII

VALUES OF RELATIVE PRECISION INDEX

Sample Size n	Precision of the Production Process		
	Low	Medium	High
2	Below 5·4	5 4 to 7 2	Above 7 2
3	„ 3 6	3 6 „ 4 8	„ 4 8
4	„ 3 0	3 0 „ 4 0	„ 4 0
5	„ 2 7	2 7 „ 3 6	„ 3 6
6 or 7	„ 2 4	2·4 „ 3 2	„ 3 2
8 to 10	„ 2 1	2 1 „ 2 8	„ 2·8
State of production*	Production of defectives inevitable	No production of defectives provided the sample average is in control	Production of defectives improbable

* *N.B* —In all cases it is assumed that the sample range is in control

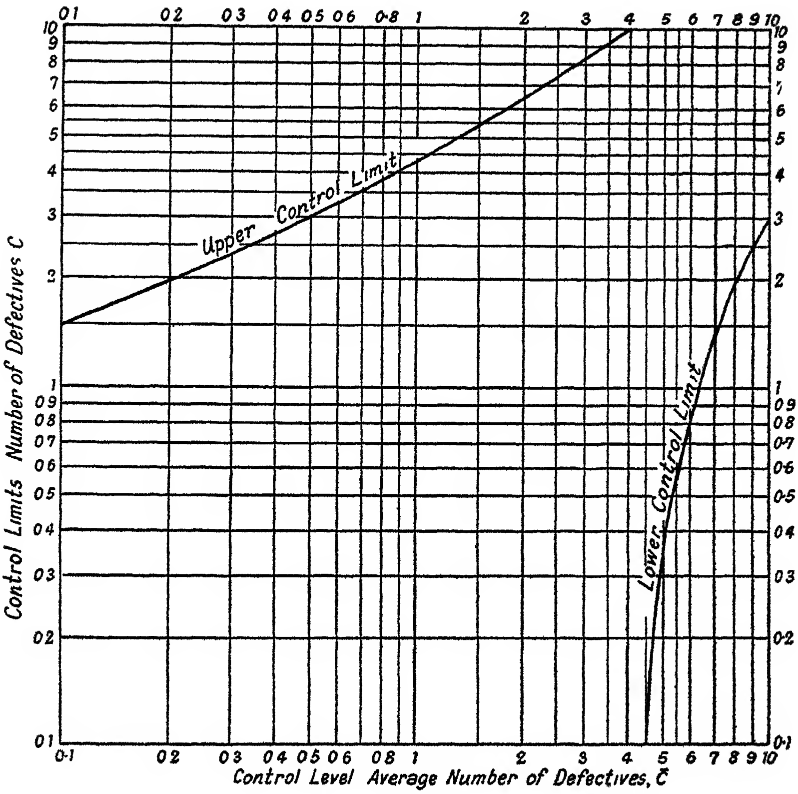


CHART I

CONTROL LIMITS FOR NUMBER DEFECTIVE, c

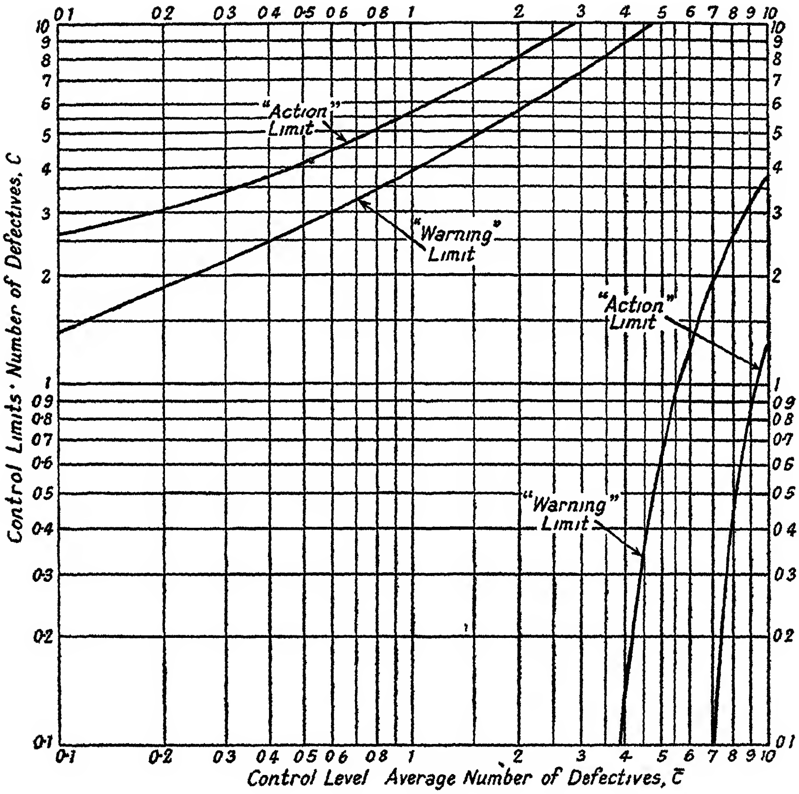


CHART II

INNER AND OUTER LIMITS FOR NUMBER DEFECTIVE, c

APPENDIX C

ESTIMATION OF PERCENTAGE DEFECTIVE FROM CONTROL CHARTS

If the production process is in control, that is, if all sample averages $\bar{x}$ and sample ranges w fall within their respective control limits, it is possible to estimate the percentage of future product which will lie outside the drawing limits $(D \pm T)$ when the relative precision of the process is low (see Appendix B, Table VIII). In practice two cases have to be considered, viz. :—

(1) where the transgression of either drawing limit is permissible, and
(2) where the product must be scrapped if the piece part dimension should fall outside one of the two drawing limits.

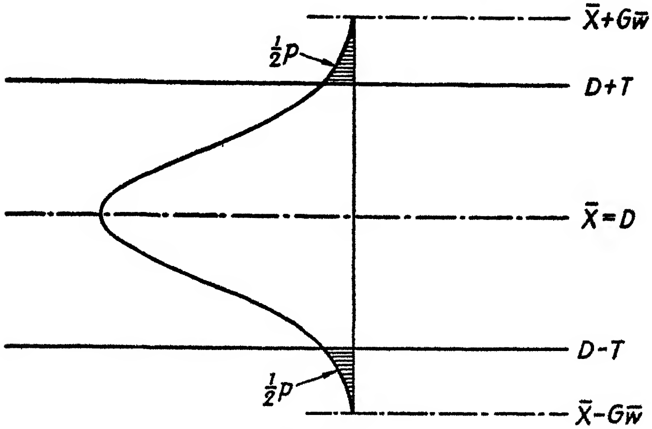


Fig. 56

Case (1). The most economical use of the drawing tolerance is made when the production process is controlled so as to make the process average $\bar{X}$ coincide with the nominal dimension D. In this case the control limits $(\bar{X} \pm A\bar{w})$ are placed symmetrically with respect to the drawing limits, and the latter thus cut off equal tails of the production characteristic, which in turn are symmetrically located and terminate at the stability limits $\bar{X} \pm G\bar{w}$. In other words, the percentage of defective product is equally divided between "high" and "low" rejects. This situation is illustrated in Fig. 56, in which the two shaded areas jointly represent the percentage p of defective items produced.

To estimate p from the control chart data first calculate the relative precision index of the process (R.P.I $=2T/\bar{w}$). Referring to Chart III, select the line corresponding to the given sample size n and read off the value of the quantity t* against the calculated R.P.I value Then refer this value of t to Chart IV and read the required percentage defective p off the curve.

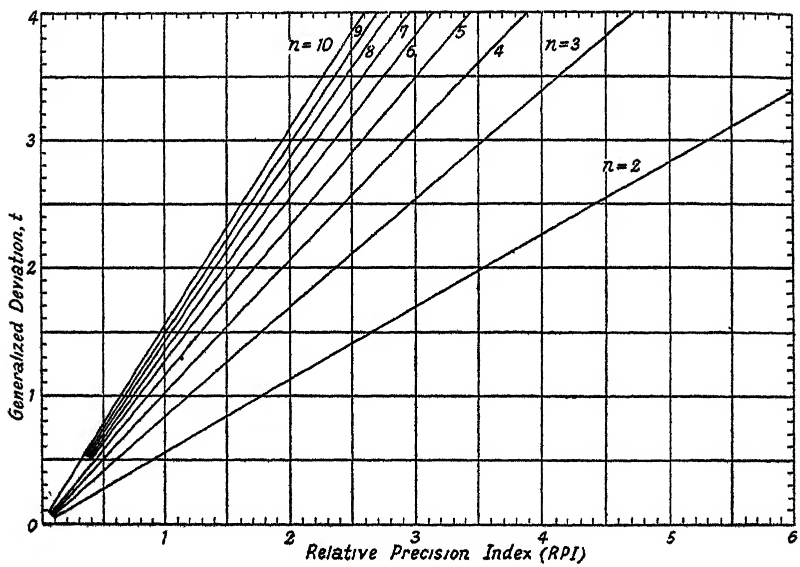


CHART III

* The variable t, commonly known as the generalised (or standardised) deviation, is that of the Normal frequency distribution $\varphi(t)=\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}t}$

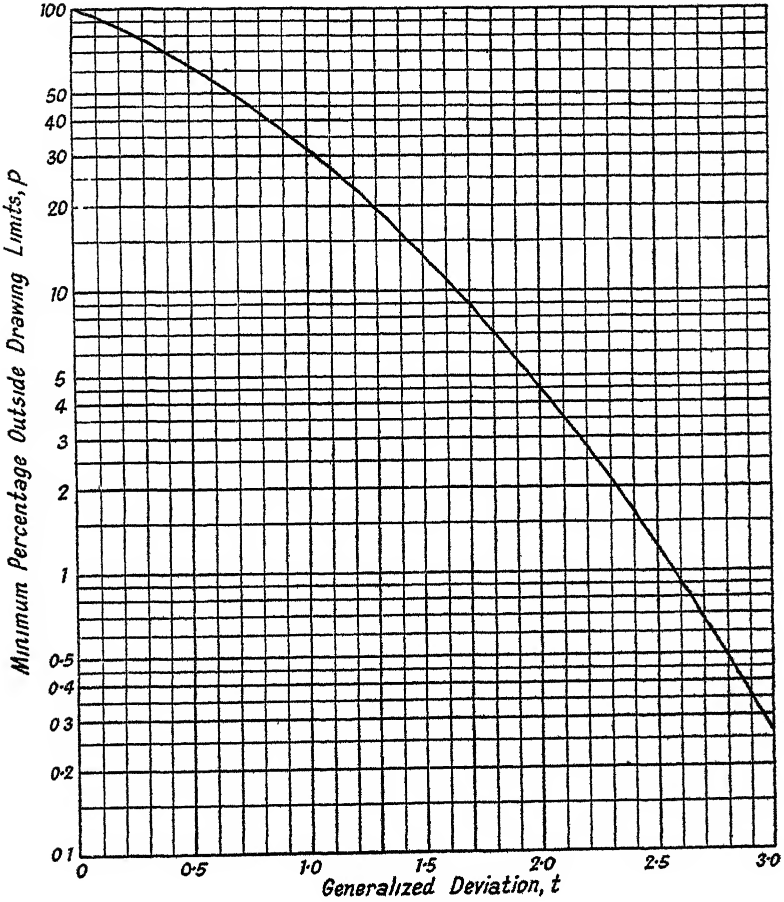

Minimum Percentage Outside Drawing Limits, p
100
50
40
30
20
10
5
4
3
2
1
0·5
0·4
0·3
0·2
0·1
0
0·5
1·0
1·5
2·0
2·5
3·0
Generalized Deviation, t

CHART IV

Case (2). The situation arising in this case is illustrated in Fig. 57. Diagram (*a*) shows the case where the lower drawing limit may not be exceeded, so that only "high" rejects are allowed to occur. Diagram (*b*) depicts the converse case where only "low" rejects are permissible

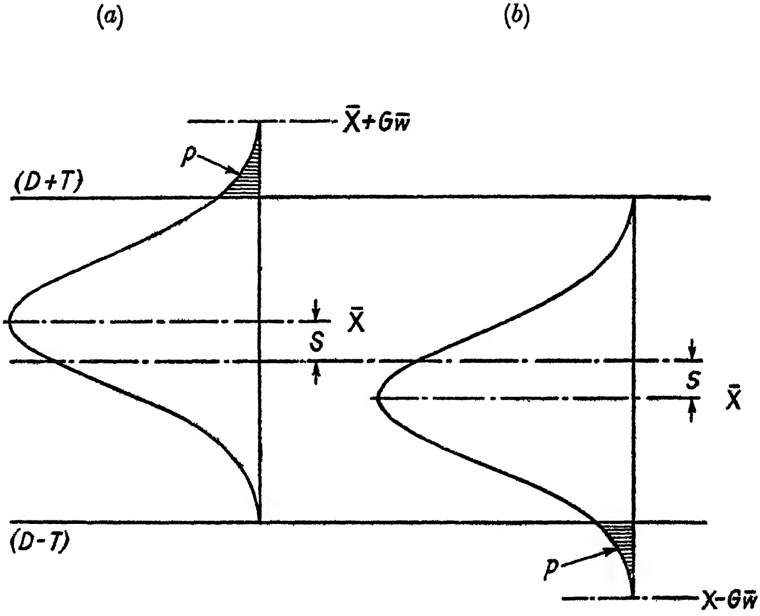


Fig. 57

Practical examples of these are the machining of external and internal diameters respectively. It is evident from Fig. 57 that in both cases the aimed-at dimension (i e., the process average $\bar{X}$) must be off-set from the nominal dimension midway between the drawing tolerances.

The amount of this off-set S, expressed as a fraction of the semi-tolerance T, is given by

$$\frac{S}{T}=\left(\frac{\text{Critical R.P.I.}}{\text{Actual R P I.}}\right)-1 \quad \ldots \quad \ldots \quad \ldots \quad \ldots .(13)$$

Values of the critical R.P.I. for different sample sizes n are given in Table III on p 45. The actual R P I. value is calculated from the control chart data in the usual way. The process average is then given by $\bar{X}=(D+S)$ or $\bar{X}=(D-S)$ as the case may be, and the control limits on the chart for sample averages $\bar{x}$ are placed as usual at $(\bar{X}\pm A\bar{w})$.

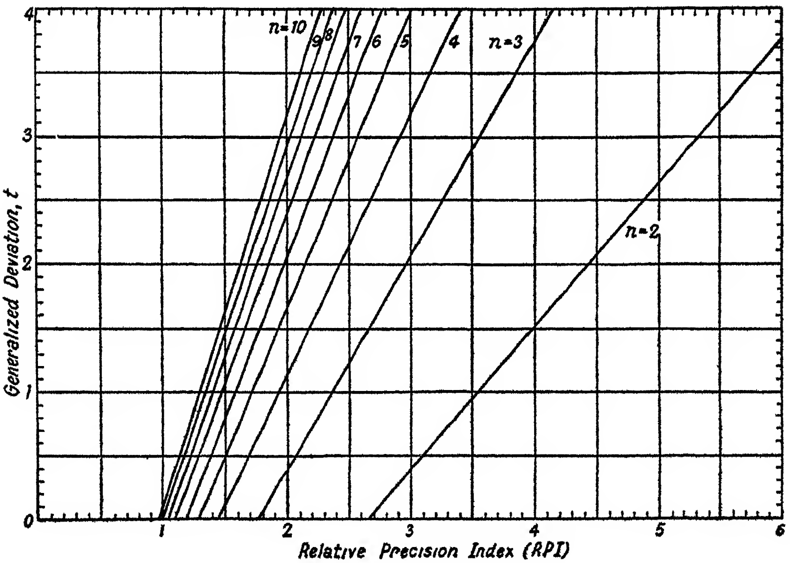


CHART V

To estimate the percentage of defectives p, shown by the shaded areas in Fig. 57, refer to Chart V and, selecting the line corresponding to the given sample size n, read off the value of t against the actual R.P.I. value calculated from the control chart data. Then refer this value of t, as before, to Chart IV and read the required percentage p off the curve.

APPENDIX D

QUALITY CONTROL IN THE MACHINE SHOP

The following instructions have been taken from the quality control routines issued in 1940 by the production and inspection departments of Messrs. Creed & Co, Ltd, for the use of operating personnel in their machine shops. The relevant inspection record cards and control charts are described in Chapter VI (see Figs. 32 to 35 inclusive).

1. **Instructions to the Quality Control Records Section.** The function of this section is to prepare, issue on demand, record and file all Process Inspection Record Cards and associated Control Charts. Preparation includes analysis of measurement recordings on Record Cards, and the drawing up therefrom of Control Charts for sample averages, ready for issue when required.

Working arrangements of this section are required to be such that all information pertaining to any process operation within the scope of the Quality Control procedure is up to date *and available for instant use.* No delay must occur in the issue of a Process Inspection Record Card and associated Control Charts when called for by the Machine Shop Inspection Section. Minimum delay in issue, and accuracy based on methodical working, are the measure of the efficiency of the Records Section.

1.1. *Preparation of Record Cards.* The first Record Card issued on any process operation is the basis on which all subsequent Record Cards are issued for the same operation on the same component. In the case of the first Record Card issued, therefore, attention must be given to :—

(*a*) The dimensions stated on the front of the Card as being of prime importance from the inspector's point of view. These will naturally include all dimensions subject to control by Control Chart, but may include some not subject to such control.

(*b*) The Special Notes on the back of the Card drawing the inspector's attention to items of secondary importance which require to be checked in addition to, or as part of, the prime dimensions.

(c) The Inspection Interval and the number of components to be examined at each inspection visit. These are based on the cycle time for the operation and should be worked out so that Patrol Inspection covers 5 to 10 per cent. of the machine output. In this connection it should be noted that Patrol Inspection is more effective if, for example, the inspector visits the machine every 45 minutes and examines two components, rather than every 90 minutes to examine four components.

Once an operation has been established, the Record Card headings as covered by (a), (b) and (c) above become permanent and are common to all Cards subsequently issued on the same operation.

1.2. *Preparation of Control Charts.* Analysis of measurement recordings on completed Record Cards provides the basis from which Control Charts are prepared. (See instruction on Record Card analysis*.) Control Charts are to be made on squared paper provided with a vertical scale for the dimension and two horizontal *black* lines representing the upper and lower engineering limits. Within these engineering limit lines are drawn two *red* lines symmetrical about the nominal, or mean, dimension and spaced apart as determined by analysis of previous measurement recordings, or as may be specified. Relevant dimensions should be filled in, and all prepared Control Charts filed in a manner convenient for issue when called for.

1.3. *Issue of Record Cards and Control Charts* Issue will be made on request by the Machine Shop Inspection Section, from whom will be required particulars of Schedule or Job No , Part No., Machine Section (i.e., Capstans, Mills or Drills, etc.), Operation No. and Batch Size. Filing arrangements should be such that the Part No. and Operation No. lead the issuing clerk to prepared Record Cards and Control Charts, which simply require filling in with respect to Job No. and Batch Size to complete them.

On issue, each Record Card and Control Chart will be given a Serial No. and the particulars entered in a serially numbered register for purposes of recording and identification.

1.4. *Filing and Indexing.* Record Cards and Control Charts will be filed in Serial No. order after return from the Machine Shop Inspection Section as operations are completed. Record Cards requiring analysis will be analysed before filing, and all particulars relevant to analysis required on the back of the cards fully filled in.

* Not included here.—H.R.

For purposes of cross reference, an Index Card should be made out for each part number On this Index Card should be entered all the operation numbers to which the part is subject, and against each operation number should appear the Serial Nos. of all the Record Cards issued. This Index Card then becomes the Master Card to which reference can be made when information is required from any or all of the Record Cards issued for a particular operation.

1.5. *Standardisation of Control Limits.* From analysis of Process Inspection Record Cards on consecutive batches of parts on any given operation, it becomes possible, if results are satisfactory, to arrive at Standard Control Limits. This, in effect, means that the process operation has proved satisfactory in actual production on a number of separate occasions, and that further analysis of inspection recordings is not necessary unless requested by those in authority. Where this stage has been reached, Record Cards and Control Charts will still be issued on subsequent batches as heretofore, with the exception that Control Charts will be made out with the Control Limits pre-set from the standard arrived at.

In order that particulars of such standard limits may be readily available for the preparation of Control Charts, the information should be entered on the Index Card for the part number in question against the operation concerned.

2. **Instructions to the "First-off" Inspector.** The function of the "First-off" inspector is to approve or reject the components first produced from a new machine set-up, and, in co-operation with the machine setter, to get production going on a sound basis from the commencement of the operation about to run.

The inspector will proceed as follows :—

2.1. On submission by the setter of the first few parts produced, the inspector will examine the parts in accordance with the requirements of the relevant drawing and/or operating layout.

2.2. In the event of the parts being incorrect to the specified requirements, the inspector will reject them and explain to the setter his reasons for rejection.

2.3. After correction to the set-up, the setter will submit further parts for examination.

2.4. The term "satisfactory" as applied to the first parts produced must be interpreted as meaning that, not only are the parts correct in respect to all specified requirements, but also have some margin to cope with normal dimensional variability such as may arise from tool wear or the settling down of stops on the machine as production proceeds.

Parts from a new set-up which are found to be on either extreme of dimensional tolerance and which do not allow for changes as production settles down, may not be considered as satisfactory.

2.5. In the event of the parts submitted by the setter being found satisfactory, as in 2.4, the inspector will —

(a) Authorise the setter to put an operator on the machine and commence production.

(b) Apply immediately to the Quality Control Records Section for a Process Inspection Record Card and Control Charts appropriate to the operation.

2.6. On receipt of the Record Card and Control Charts, the inspector will examine the specified number of parts, constituting the sample size, *as produced by the operator*, and make the *first* entries on the Record Card and associated Control Charts.

2.7. The inspector will then place the Record Card and Control Charts in the appropriate container or display board adjacent to the machine, *and notify the Patrol Inspector that production has commenced on the particular operation and is satisfactory.*

2.8. From this stage onwards the "First-off" Inspector will not be concerned with the operation in production, except that he may be required to act in an advisory or supervisory capacity in the event of trouble developing as production proceeds.

3. **Instructions to the Patrol Inspector.** The function of the Patrol Inspector is to visit the machines in his section which are in production, at regular intervals, and maintain control of quality of the components being produced as established by the "First-off" Inspector who originally approved the machine set-up and initiated the Record Card and Control Charts.

The Inspector will proceed as follows :—

3.1. On receiving notification from the "First-off" Inspector that production has commenced on a new set-up, the Inspector will visit the machine with the least possible delay and verify that the following items are in order :—

(a) That all entries required by the Process Inspection Record Card have been correctly and fully filled in by the "First-off" Inspector at the first *production* visit to the machine. (See 3.4 below.)

(b) That the first points plotted on the Control Charts are satisfactory in the sense that some margin exists for normal dimensional

variation arising from tool wear and the settling down of the machine.

3.2. The inspector will then select at random from parts just being produced, the number of parts prescribed by the Record Card as constituting the sample size, and proceed to measure or gauge them as prescribed by the Record Card

From such measurement or gauging, the inspector will immediately make the appropriate entries on the Record Card and plot the results on the Control Charts in the manner described below in 3 5.

3.3. Thereafter the inspector will regularly visit the machine in accordance with the inspection interval indicated on the record card and proceed as in 3.2 above. In this connection it must be understood that, to obtain full benefit from the Quality Control procedure in force, the following points must be constantly borne in mind —

(a) All measurements and gauging to be carried out accurately and methodically.

(b) All entries made on the Record Card to be neat, legible and, above all, *accurate.*

(c) All plotted points made on Control Charts to be neat, and *accurate as to position.*

(d) Points to be plotted on Control Charts immediately after measurement or gauging of parts.

(e) ACTION TO BE TAKEN IMMEDIATELY THE CONTROL CHARTS SHOW A DEFINITE TENDENCY TOWARDS DEFECTIVE PRODUCTION (see 3.6 and 3.7 below)

3 4. *Record Card Entries.* In essentials, the Process Inspection Record Card entries made by the inspector must give the following particulars :—

Date and time of visit to machine.

Inspector's No.	Operator's No.
Setter's No	Machine No

Individual measurements of the components in each sample examined, for all dimensions specified.

The *average* dimension of the sample components, i.e , the group average. The dimensional variation in the sample, i.e., the *range.*

The Record Card headings, filled in by the Quality Control Records Section at time of issue, indicate the dimensions affected by the operation and which must be checked by the inspector. In addition to these major checks the inspector is required to check certain minor items as indicated under " Special Notes " on the back of the Record Card.

In the "Remarks" column on the back of the Record Card, the nspector is required to enter details of action taken at any specific isit to the machine arising from any unsatisfactory condition revealed y his examination of components being produced. These entries should e brief but lucid statements of fact.

3.5. *Plotting Results on the Control Charts.* The points plotted on Control Charts for sample averages are arrived at from the *average* limension of the specified number of components *measured* by the nspector at each visit. For example, if measurement of four components ives dimensions of 0 1253 in., 0·1250 in., 0·1254 in., 0·1251 in., respecively, the average dimension of this group of four components will be 1252 in., and it is this *average* dimension which is plotted on the Control Chart appropriate to that dimension.

Control Charts for controlling dimensions checked by *gauging* as listinct from measurement, e g., a hole size check by a "Go" and "Not Go" plug gauge, are for the purpose of indicating the *proportion* of efective components found up to and including any inspection visit. uch charts indicate the *percentage* of defective components disclosed y periodic inspection of a specified number of components. In using hese charts, the inspector is required to check 5 or 10 components with he appropriate gauge at each visit, and plot the number of defective omponents found so that the chart reveals the percentage of defective omponents found up to and including the last visit.

3.6. *Interpretation of Control Charts.* On Control Charts for sample verages, plotted points falling *within* the Control Limit lines on the hart indicate a satisfactory condition In the event, however, of a lotted point falling *outside* either of the Control Limit lines immediate onsideration must be given to the matter, because such a point indicates ome disturbance in the process which may, if not attended to, give ise to the production of defective components. In the case of a plotted oint falling outside the control limits which follows a *random* scattering f points on the chart which are all *within* the control limits, it may be hat this is a freak condition which merits no other action than further xamination of components just coming off the machine. Where owever, a plotted point falling outside the control limits follows a learly defined upward or downward trend in the pattern of the points n the chart, this is an indication of a definite change in the machine et-up or its operation *and is a situation which demands corrective action mmediately.* (See also Section 6 below.)

In such an event, the inspector must stop production immediately and acquaint the machine setter of the facts. Production may be allowed to continue only after satisfactory corrective action has been taken by the setter.

Similarly, if the Control Chart for Proportion Defective in the case of gauged components shows that the percentage of defective components exceeds the predetermined control limit, action must be taken immediately to correct the cause of defective production

3.7 *Significance of Range.* Range is the difference between the highest and lowest measurement recorded in the inspection of components comprising a sample group. For a satisfactory condition, the range must never exceed the dimensional tolerance allowed by the engineering or drawing limits. For example, if the nominal dimension of a component is 0·125 in. and the engineering limits are $\pm 0{\cdot}002$ in., the range within a sample group must never exceed 0·004 in. It is possible to obtain a sample average dimension which will give a plotted point within the control limits of the chart, *coincident with excessive range.* For this reason it is necessary for the inspector to pay as much attention to dimensional range within a sample group as that which he is required to give to the position of the average dimension of the group when plotted on the Control Chart *In cases where excessive range persists, corrective action is indicated as being necessary and must be taken.*

3.8. *Significance of Control Limits in Relation to Engineering Limits.* In order to avoid any misunderstanding between inspection and production personnel, it should be made clear by the inspector to setters and operators that Quality Control does not rob them of the dimensional variation allowed by the engineering limits appearing on a drawing or operation layout. All components produced which are anywhere within the engineering limits specified are satisfactory. The purpose of the control limits set on the Control Charts is to enable early note to be taken of any tendency in an operation to depart from satisfactory production and reach a stage where components produced will be outside the engineering limits. The control limits bear a definite relation to engineering limits in the sense *that they are based on satisfactory production previously obtained and serve to control production that has already been proved to be controllable.*

4. Instructions to Foremen and Setters. While it should be understood that Quality Control is primarily the concern of the Inspection Department, it is none the less essential that production personnel

should be clear as to the ultimate object of Quality Control and the part played in the matter by those whose main concern is output.

The fundamental object of Quality Control is to stabilise all process operations, and keep defective production at a minimum through control of the process operations during actual production.

Foremen and setters can play an effective part in achieving this object by interest and co-operation. This can best be shown by —

(*a*) Studying the control charts and learning to interpret from them the position relating to any particular operation.
(*b*) Enlisting the interest and co-operation of the operators, and giving them clear instructions.
(*c*) Co-operating with the inspector when he asks for corrective action to be taken when the control charts show a tendency towards defective production , in other words, not waiting *until defective production is an accomplished fact* before taking action.

Finally foremen and setters should understand that Quality Control does *not* rob them of the full scope of dimensional variation allowed by engineering or drawing limits What it does do, is to draw instant attention to a tendency for production to depart from the engineering limits in time for effective corrective action to be taken.

5. **Instructions to Machine Operators.** Quality Control is a matter of interest just as vital to operators as to any other individuals or section in a works organisation. No operator can afford to stand aloof and regard Quality Control as a matter outside his or her sphere of interest, or as something not to his or her personal advantage.

From this point of view the attention of operators is drawn to the following points which affect the part they play in the scheme of engineering production, and the assistance they can give to Quality Control .—

5.1 The only parts that count are *good* parts. Defective parts mean wasted effort and represent a financial loss to the operator as an individual as well as to the firm as a whole.

5.2. Defective parts can and do result from :—

Lack of interest.
Carelessness.
Inattention to instructions.
Irresponsibility.

5.3. If a machine is set correctly, gauges are provided and gauging time is allowed for, and clear instructions have been given by the setter,

the quality of production from then onwards is very largely in the hands of the operator, *and should be a matter of interest to the operator no less than the quantity of parts produced*

5.4. The inspector should be regarded by the operator as someone pulling on the same rope, and with the same ultimate object in view, that is, the production of good parts in good quantity.

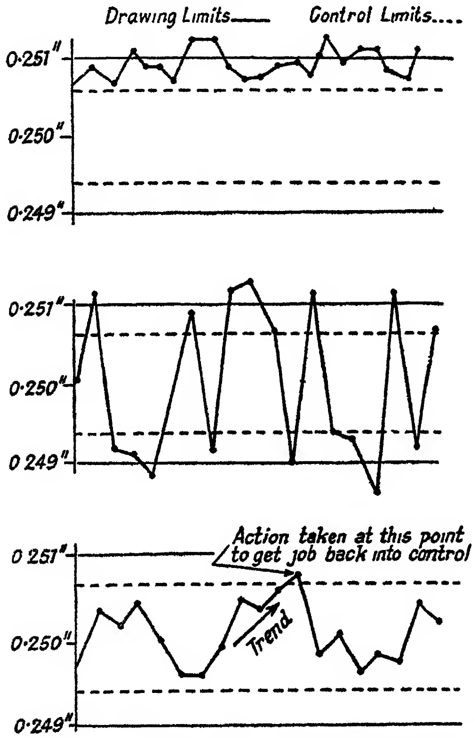
5 5. Operators should see in the inspector a helpmate and adviser. They can show that they regard him as such by taking a personal interest in the inspector's control charts and asking questions about what the charts reveal concerning their work and what they, as operators, can do to improve the job if it is not wholly satisfactory.

6. **Making Quality Control Effective.** The purpose of Quality Control as applied to machine-shop processes is to prevent the production of defective components, and the Quality Control procedure in use has been devised with the specific object of obtaining the maximum efficiency from all productive effort expended in the machine shops. The less scrap produced, and the fewer the components that are passed off from any operation and subsequently found to need rectification, the higher will this efficiency be.

In order to obtain the desired results, it is very necessary that particular attention should be paid to the conditions prevailing with respect to any machining operation as revealed by the associated control chart. The purpose of the control chart is to present the facts relating to the operation concerned, and to give immediate warning when any disturbance is at work in the manufacturing process which may lead, or which has already led, to the production of defective components. If the warning given by the control chart is ignored, then its value is completely lost and productive efficiency will suffer accordingly.

The accompanying illustration, Fig. 58, gives examples of two control charts which have failed in their purpose, and one which has been interpreted correctly and its purpose made effective. Example 1 shows that the operation started with the production of components dangerously near the upper dimensional limit, and that the batch was allowed to run under conditions that must have produced a large proportion of oversized components. Example 2 reveals some serious disturbance in the process operation that gave rise to wide dimensional variations in the component produced In both these cases action should have been taken to correct the machine set-up *at the first indication of trouble,* rather than let the jobs run when something was obviously wrong. Example 3 is typical of a control chart that is used effectively.

Warning is given when the process is tending to run out of control, and action is taken to correct the cause of trouble in time to prevent defective production Only by interpreting control charts correctly, and by taking the necessary action as and when indicated, can Quality Control be made an *effective* procedure.



Example 1.
In this case the dimensional variation is satisfactory but the job has been allowed to start above the upper control limit and remain that way for the run of the batch without any action being taken to correct what is obviously a bad set-up.

Example 2.
This represents a bad case Excessive dimensional variation is indicated, and the job is absolutely out of control There is something fundamentally wrong with the machine set-up when results like this are obtained

Example 3.
This shows a job running under control, with effective action taken when indications are given that some disturbance is at work which may lead to defective production if not looked for and eliminated.

Fig. 58. INTERPRETATION OF CONTROL CHARTS

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